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TIMBER ENGINEERING
FOR DEVELOPING COUNTRIES

Part 1

Introduction to Wood and Timber Engineering*

Prepared by

Agro-industries Branch,
Division of Industrial Operations

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PREFACE

The United Nations Industrial Development Organization (UNIDO) was established in 1967 to assist developing countries in their efforts towards industrialization. Wood is a virtually universal material which is familiar to people world-wide, whether grown in their country or not. Wood is used for a great variety of purposes but principally for construction, furniture, packaging and other specialized uses such as transmission poles, railway sleepers, matches and household woodenware. UNIDO has the responsibility within the United Nations' system for assisting in the development of secondary woodworking industries, and has done so since its inception, at national, regional and interregional levels through projects both large and small. UNIDO also assists through the preparation of a range of manuals dealing with specific topics of widespread interest which are common to most countries' woodworking sectors.[1/]

The lectures comprising this set of documents are part of UNIDO's continuing efforts to help engineers and specifiers appreciate the role that wood can play as a structural material. Part 1 consists of 6 out of the 36 lectures prepared for the Timber Engineering Workshop (TEW) held 2 - 20 May 1983 in Melbourne, Australia. The TEW was organized by UNIDO with the co-operation of the Commonwealth Scientific and Industrial Research Organization (CSIRO) and funded by a contribution made under the Australian Government's aid vote to the United Nations Industrial Development Fund. Administrative support was provided by the Australian Government's Department of Industry and Commerce. The remaining lectures are reproduced as Parts 2 to 5 covering a wide range of subjects, including case studies, as shown in the list of contents.

[1/] A fuller summary of these activities is available in a brochure entitled "UNIDO for Industrialization, Wood Processing and Wood Products", PI/78.

These lectures were complemented by site and factory visits, discussion sessions and assignment work done in small groups by the participants following the pattern used in other specialized technical training courses in this sector - notably in furniture and joinery production[1/] and on criteria for the selection of woodworking machinery[2/].

It is hoped that publication of these lectures will contribute to greater use of timber as a structural material to help satisfy the tremendous need for buildings: domestic, agricultural, industrial and commercial as well as for particular structures, such as bridges, in the developing countries. It is also hoped that this material will be of use to teachers in training institutes as well as to engineers and architects in both public and private practice.

Readers should note that examples cited are often of Australian conditions and may not be wholly applicable to developing countries despite the widespread use of the Australian timber stress grading and strength grouping systems and the range of conditions encountered in the Australian subcontinent. Readers should also note that the lectures were usually accompanied by slides and other visual aids, together with informal comments by the lecturer, for added depth of coverage.

The views expressed are those of the individual authors and do not necessarily reflect the views of UNIDO.

[1/] Lectures reproduced as ID/108/Rev.1.

[2/] Lectures reproduced as ID/247/Rev.1.

CONTENTS

TIMBER ENGINEERING FOR DEVELOPING COUNTRIES

Part 1

Introduction to Wood and Timber Engineering

Original lecture numbers			Page
1A	Forest Products Resources	W. E. Hillis	3
1B	Timber Engineering and its Application in Developing Countries	John G. Stokes	16
2	Wood, the Material	W. E. Hillis	29
3	Mechanical Properties of Wood	Leslie D. Armstrong	57
15	Conversion of Timber	Mervyn W. Page	99
16	Seasoning of Structural Timber	F. J. Christensen	111

Part 2

Structural Timber and Products

Original lecture numbers			Page
4	Characteristics of Structural Timber	Robert H. Leicester	
5	Structural Grading of Timber:		
5(a)	Structural Grading of Timber	William G. Keating	
5(b)	Proof Grading of Timber	Robert H. Leicester	
5(c)	Model of the Timber Grading Process	Robert H. Leicester	
6	Visual Grading of Timber	J. Hay	
22	Review of Timber Strength Systems	William G. Keating	
7	The Properties and End Uses of a Range of Wood-based Panel Products	Kevin J. Lyngcoln	
8	Structural Plywood	Lam Pham & Robert H. Leicester	
14	Glued Laminated Timber	Robert H. Leicester	
10	Adhesives for Timber	R. E. Palmer	

Part 3

Durability and Fire Resistance of Timber

17 Durability of Timber — John Beesley
21 Fire Resistance of Timber — Robert H. Leicester

Part 4

Strength Characteristics and Timber Design

11 The Fracture Strength of Wood — Robert H. Leicester
12 Timber Connectors — Edward P. Lhuede & Robert H. Leicester
13 Buckling Strength of Timber Columns and Beams — Robert H. Leicester
20 Derivation of Design Properties — Robert H. Leicester
25 Examples of the Use of AS 1720-1975 SAA Timber Engineering Code Standards Association of Australia — Prepared by Robert H. Leicester
26 Wind Resistance of Timber Buildings — Greg F. Reardon
27 Earthquake Resistance of Timber Buildings — G. B. Walford
28 Load Testing of Structures — Robert H. Leicester

Part 5

Applications and Constructions

24 Specification of Timber for Structural Use — William G. Keating
9 Plywood in Concrete Formwork — Kevin J. Lyngcoln
18 Timber Structures - Detailing for Durability — Leslie D. Armstrong
19 Use of Green Timber in Structures — Leslie D. Armstrong
29 Pole Structures — G. B. Walford
23 Timber Framing for Housing — Bernie T. Hawkins
30 Case Study of Timber Construction - Kenya Hotel — Peter A. Campbell
31 Case Study of Timber Construction - New Zealand — G. B. Walford
32 Case Study of Timber Construction - South East Asia — John R. Tadich
33 Stress Grades and Timber Construction Economies, exemplified by the UNIDO Prefabricated Timber Bridge — C. R. Francis
34 Efficient Timber Structures Using Metal Connectors — E. E. Dagley
35 Construction Experiences in Developing Countries — C. R. Francis

INTRODUCTION

Many developing countries are fortunate in having good resources of timber but virtually all countries make considerable use of wood and wood products, whether home-grown or imported, for housing and other buildings in both structural and non-structural applications, as well as for furniture and cabinet work and specialized uses. It is a familiar material, but one that is all too often misunderstood or not fully appreciated since wood exists in a great variety of types and qualities.

There are certain well-known species that almost everyone knows of, such as teak, oak and pine, while some such as beech, eucalyptus, acacia, mahogany and rosewood are known primarily in certain regions. Others have been introduced to widespread use more recently, notably the merantis, lauans and keruing from Southeast Asia. Plantations also provide an increasing volume of wood. Very many more species exist and are known locally and usually used to good purpose by those in the business.

The use of timber for construction is not new and, in fact, has a very long tradition. This tradition has unfortunately given way in many countries to the use of other materials whose large industries have successfully supported the development of design information and teaching of engineering design methods for their materials - notably concrete, steel and brick. This has not been so much the case for timber despite considerable efforts by certain research and development institutions in countries where timber and timber-framed construction has maintained a strong position. Usually their building methods are based on the use of only a few well-known coniferous (softwood) species and a limited number of standard sizes and grades. Ample design aids exist and relatively few problems are encountered by the very many builders involved.

Recently, computer-aided design has been developed along with factory-made components and fully prefabricated houses with the accompanying improvement in quality control and decreased risk of site problems. Other modern timber engineering developments have enabled timber to be used with increasing confidence for an ever wider range of structures. This has been especially so in North America, Western Europe, Australia and New Zealand.

UNIDO feels that an important means of transferring this technology is through the organization of specialized training courses aimed at introducing engineers, architects and specifiers to the subject and especially drawing to their attention the advantages of wood (as well as disadvantages and potential problem areas) and reference sources so that for particular projects or structures, wood may be fairly considered in competition with other materials and used when appropriate. Cost comparisons, aesthetic and traditional considerations must naturally be made in the context of each country and project but it is hoped that the publication of these lectures will lead those involved to a rational approach to the use of wood in construction and remove some of the misunderstandings and misapprehensions all too often associated with this ancient yet modern material.

Material in this publication may be freely quoted or reprinted, but acknowledgement is requested together with two copies of the publication containing the quotation or reprint.

FOREST PRODUCTS RESOURCES

W. E. Hillis[1/]

About one-third of the earth's land surface has conditions which are suitable for the growth of forests and these conditions are usually also the most suitable for habitation. Consequently from the beginning, there has been continual conversion of forests by humans to other uses but only recently has this conversion rate become significant. Large areas of forests have been removed in the temperate regions but that situation has stabilised and the forests continue to produce a significant portion of local needs. Now the removal of forests is accelerating in the tropical and sub-tropical regions where the population increase is rising rapidly. These latter regions have provided and can continue to provide timber for local use and for export but from many species having properties different from those of timbers of temperate regions.

Forests provide both materials and energy. Over one-half the wood felled globally is used for fuel. In some countries the proportion is over 90% and the high consumption of trees is leading to the denudation of the soil and other changes. Over 1.3 billion people are reportedly suffering from an acute scarcity or deficit of fuelwood and will, by the year 2000 increase to 3 billion people. There is an estimated minimum need of up to 3 billion m^3 of fuelwood and an estimated shortfall of nearly 1 billion m^3 annually.

Forest products are the third most important commodity by weight in the USA and a major one in all countries. Furthermore, they consume less energy in processing than other materials, they are less polluting, renewable and so on. The demand for forest products is likely to increase with attempts to replace materials that require high amounts of energy, are non-renewable, and cause pollution.

The world production of wood per capita peaked in 1976 (at 0.67 m^3) and has steadily declined (to less than 0.60 m^3) so that attention to the amount of resources available is necessary.

[1/] An officer of CSIRO, Division of Chemical and Wood Technology, Melbourne, Australia.

Considerable advances in the availability of comprehensive information recently became available with FAO Forestry Papers Nos 29 and 30. These papers point to the difficulties in gaining accurate comparable data from complex situations and advise caution in dealing with their detailed figures. Much of the data given in this present paper are taken from FAO No. 29 and 30 and similarly caution in the use of the data of some countries is necessary. Some of the discrepancies between figures could be due to the policy of the FAO team (Paper No. 29) to force a balance between consumption and supply in global terms on the basis that a shortage of forest products will raise the price which will reduce demand.

The recent and projected future consumption of industrial wood products for the major regions is given in Table 1 and the estimated demand for wood to supply those products is given in Table 2. The total demand (Table 2) may be excessive as residuals from the sawlog estimates are used in variable amounts to provide some of the needs for fibre. Nevertheless, higher demands for the year 2000 have been estimated by some observers. It is unlikely that current forest resources can provide, on a sustained basis, the higher estimates of global needs of forest products for the year 2000.

The availability of forest products differs from region to region (Table 3) and international trade has been able, in the past, to meet demands. The needs will be higher in the year 2000 (Table 4). The proportion of the supplies of industrial softwood and hardwood from different regions is given in Table 5.

A number of claims have been made of the potentially large 'wood baskets' in tropical countries. Many of the soils of these forests are thin and of low fertility so that regeneration of the forests after harvesting from these forests will be slow and they are in a sense nonrenewable. Decisions to remove trees will need to be carefully made. Also, the areas of productive forests are much less than expected. In 1980 there were in the tropical regions about 1.2 billion hectares of closed forest (97% hardwoods) but only 670 million hectares of productive closed forests over 60 years of age (considered to be the minimum harvesting age), untouched and accessible for use. Few of the forests have reliable inventories (let alone management plans) so that the availability of forest products is uncertain. Less than 15 thousand billion m³ total growing stock exist in the productive closed forests and their growth rates are mainly below 2 m³/ha/yr (Table 6). The productivity of these forests is very low (Table 7).

Few trees of the secondary tropical species yield logs of suitable shape or size for economic conversion to solid wood products even when they are accessible for harvesting. Furthermore big losses in recovery can result from low wood quality such as the presence of decay, discoloration, reaction wood, brittle heart, very high and very low density woods, rapid deterioration of fallen logs in tropical climates, abrasive woods and general variability within and between logs. Quality is lower in partly utilised forests. Lumber from secondary species faces the problems with marketing material of unfamiliar and variable properties and international standards that are framed for the use of familiar species from temperate climates. All these obstacles result in the current wastages.

Tropical America has 68% of undisturbed productive closed broadleaved forests (tropical South America 65% and mainly in the Amazon Basin), tropical Africa 18%, whereas tropical Asia with its huge population only 14%. It has been estimated the average annual production of industrial wood from tropical countries in the 1983 to 1987 period will be 215 million m³ with 37.5% coming from American countries, 24.1% from Africa and 51.2% from Asia.

Renewal of these forests is rapidly falling behind deforestation (Table 8). However, high growth rates exceeding 35 m³/ha/yr have been achieved in some of the plantations that have recently been established, but the quality of the wood from these sources will differ from that obtained from slow-grown trees of the same species. In time, wood of superior quality should be obtained.

The need for forests and their products depends on population. The world population of about 4 billion in 1975 was mainly in the Asia-Oceania region (about 56%) following by Europe (14%), Africa (10.5%), South America (7%), USSR (6.7%) and North America (6.3%). It has been estimated the population will grow to more than 6 billion by the year 2000 and to 10 billion by 2030. About 90% of the population increase will take place in the poorest tropical regions, where half the global forests exist, and mainly in Africa, followed by South America and then Asia (Table 9).

The other major reserve of forest products is in the USSR which is the major producer and consumer of softwood lumber and has timber reserves exceeding 75 billion m³ with an annual increment of 575 million m³, most of which is in the taiga regions of the Siberian and Soviet far-east forests containing an estimated 70% of the world's conifers. These vast resources which are being harvested at well over 1 million ha/yr suffer from very slow growth rates, difficulties in regeneration, poor accessibility (for about 36% of the area) and remoteness. Currently more than 300 million m³ of industrial wood are cut annually and mainly in the Ural region. The established plantations cover an area of 5.2 million ha and are being increased at a rate of 800,000 to 900,000 ha/yr and they are being managed on 80 to 100 year rotations. The USSR plans to supply 447 million m³ of industrial wood from all its resources in the year 2000.

Some tentative estimates of supplies available in other regions are given in Table 10.

It is expected the increase in demand for softwood sawlogs will be at a 1.2% level annually between 1980 to 2000. Supplies to meet the projected growth from 676 to 862 million m³ in 2000 should be adequate but they are expected to be tight in the developed economies. However, the demand for softwood fibrelogs is projected to increase 2.3% annually. Consequently the output of both softwood sawlogs and fibrelogs is expected to be stretched close to their physical supply limits by 2000.

The world consumption of industrial wood from hardwoods is expected to rise from 443 million m³ to 673 million m³ in 2000 or at a rate of 2.1%; more than half of this will be for pulp preparation. It is expected there will be insufficient residuals to meet the demands for reconstituted boards.

In the absence of widespread disasters such as disease, insect attack and fire, there appear to be sufficient supplies to meet global needs in the year 2000 although some regional supplies will be inadequate. Beyond that time the supplies of forest products for materials and fuel for different regions will become increasingly inadequate. Alternative materials are likely to be more costly. Accordingly, in view of the long growth period required for trees, greater efforts to increase the area and yield of forests and plantations for the sustained supply of wood are now needed. Furthermore, increased attention must be given to the improvement of the conversion yields of wood from trees and to the efficiency of the use of wood in various applications.

REFERENCES

FAO Forestry Paper No. 29 (1982). World forest products; demand and supply 1990 and 2000.

FAO Forestry Paper No. 30 (1982). Tropical forest resources (by J-P Lanly).

TABLE 1
CONSUMPTION FOR THE YEARS 1980, 1990, 2000
INDUSTRIAL WOOD PRODUCTS(1)

Region	Product								
	Sawnwood (million m^3)			Wood-based panels (million m^3)			Paper (million m')		
	1980	1990	2000	1980	1990	2000	1980	1990	2000
WORLD	455	520	570	109	141	169	180	256	357
Developed Market	246	271	284						
Economies	2	2	2	84	106	122	139	189	253
North America	118	129	133	41	50	55	70	92	120
Western Europe	74	81	86	30	40	49	46	61	79
Oceania	7	7	8	1	2	2	3	4	6
Other	47	54	57	11	14	16	20	32	48
Developing Market Economies	46	69	90	6	11	18	17	29	53
Latin America	17	22	27	3	5	8	9	15	26
Africa	5	6	10	1	2	3	2	3	4
Near East	6	8	9	1	2	3	2	5	11
Far East	18	33	45	1	2	4	5	8	13
Centrally Planned Economies	163	181	199	19	24	30	24	37	56
USSR, E.Europe	141	154	167	17	21	26	17	25	39
Asia	22	28	32	2	3	4	7	12	17

(1) Taken from FAO Forestry Paper No. 29 (1982)

TABLE 2
ESTIMATED DEMAND FOR WOOD (in million m^3) TO SUPPLY INDUSTRIAL WOOD PRODUCTS(1)

Region	Product									Total		
	Sawnwood			Wood-based panels			Paper					
	1980	1990	2000	1980	1990	2000	1980	1990	2000	1980	1990	2000
WORLD	864	988	1083	174	226	270	504	717	1000	1542	1931	2353
Developed Market Economies	467	515	540	134	170	195	389	529	708	990	1214	1443
North America	224	245	253	66	80	88	196	258	336	486	583	677
Western Europe	141	154	163	48	64	78	120	171	221	309	389	462
Oceania	13	13	15	2	3	3	8	11	17	23	27	35
Other	89	103	108	18	22	26	56	90	134	163	215	268
Developing Market Economies	87	131	171	10	18	29	48	81	148	145	230	348
Latin America	32	42	51	5	8	13	25	42	73	62	92	137
Africa	9	11	19	2	3	5	6	8	11	17	22	35
Near East	11	15	17	2	3	5	6	14	31	19	32	53
Far East	34	63	85	2	3	6	14	22	36	50	88	127
Centrally Planned Economies	310	344	378	30	38	48	67	104	157	407	486	583
USSR, E.Europe	268	292	317	27	34	42	48	70	109	343	396	468
Asia	42	53	61	3	5	6	20	34	48	51	92	115

(1) Calculated from data in FAO Forestry Paper No. 29 (1982)

TABLE 3
FOREST RESOURCES AND UTILIZATION IN 1974 to 1976 (1)

Region	Forest area 1975		Apparent annual consumption		Net trade		
	Closed forest	Other woodland	Industrial roundwood for processing	Forest products in roundwood equivalent	Industrial roundwood	Processed wood (in roundwood equivalent)	Total (in roundwood equivalent)
	Million hectares		. . . . million m³. . . .		Imports-	Exports+	
WORLD	2 860	1 070	1 185	1 185			
Developed Market Economies	693	243	732	763	-44	-31	-75
North America	510	120	412	390	+22	+22	+44
Western Europe	108	18	208	250	-18	-42	-60
Oceania	50	100	17	18	+ 3	- 1	+ 2
Japan	25	-	86	95	-50	- 9	-59
Other	-	5	9	10	- 1	- 1	- 2
Developed Market Economies	1 222	642	109	100	+32	+ 9	+41
Africa	203	360	10	12	+ 5	-	+ 5
Latin America	695	180	47	47	-	-	-
Far East	310	35	46	32	+27	+14	+41
Near East	14	67	6	12	-	- 6	- 6
Centrally Planned Economies	945	185	344	322	+12	+22	+34
USSR, E.Europe	815	135	287	265	+12	+22	+34
Asia	130	50	57	57	-	-	-

(1) Adapted from FAO Forestry Paper No. 29 (1982)

(2) Includes, in addition to wood for processing, roughly 10 per cent of miscellaneous industrial wood, e.g. pitprops, poles, pilings normally used in the round; more than half is consumed in centrally planned economies

TABLE 4
ESTIMATES OF WOOD REMOVALS AND UTILIZATION IN THE YEAR 2000(1)

Region	Removal of industrial wood	Apparent consumption		Net trade		
		Industrial roundwood for processing	Forest products in roundwood equivalent	Industrial roundwood	Processed wood (in roundwood equivalent)	Total (in roundwood equivalent)
	million m³					
				Imports-	Exports+	
WORLD	2 085	1 930	1 930	-	-	-
Developed Marked Economies	1 093	1 138	1 190	-78	-52	-130
North America	642	617	581	+10	+36	+48
Western Europe	320	325	384	-16	-59	-75
Oceania	58	41	30	+16	+11	+27
Japan	58	143	175	-86	-32	-118
Other	15	12	20	- 2	- 8	-10
Developed Market Economies	365	274	238	+44	+36	+80
Africa	60	28	21	+10	+ 7	+17
Latin America	124	108	98	+ 5	+10	+15
Far East	161	128	96	+29	+32	+61
Near East	20	10	23	-	-13	-13
Centrally Planned Economies	627	518	502	+34	+16	+50
USSR, E.Europe	531	444	428	+34	+16	+50
Asia	96	74	74	-	-	-

(1) Taken from FAO Forestry Paper No. 29 (1982)

TABLE 5
SUPPLY OUTLOOK FOR INDUSTRIAL ROUNDWOOD IN THE YEARS 1980 AND 2000 FROM DIFFERENT REGIONS(1)

Amount supplied by	Softwood		Hardwood	
	1980 %	2000 %	1980 %	2000 %
North America	38.8	34.2	23.0	24.0
Western Europe	17.7	16.4	16.0	14.0
Japan	2.5	3.5	3.0	1.0
Latin America	2.2	4.4	7.0	9.0
Asia, Africa, Oceania	2.5	5.0	30.0	35.0
Centrally planned economies	36.3	36.3	21.0	17.0
Interregional shipments (in million m³)				
Sawlogs	22.7	32.3	24.8	18.8
Pulpwood	18.6	28.0	6.7	24.4

(1) Taken from FAO Forestry Paper No. 29.

TABLE 6
TOTAL GROWING STOCK ESTIMATED AT END 1980 CLOSED FORESTS (BROADLEAVED AND CONIFEROUS)
(in billion m³)

Tropical Region in	Productive			
	Unmanaged		Managed	Total
	Undisturbed	Logged		
America (23 countries)	71.3	7.2	0.02	78.6
Africa (37 countries)	30.3	8.2	0.2	38.8
Asia (16 countries)	21.2	6.6	3.6	31.4
Total (76 countries)	123.0	22.0	3.8	149.0

(1) Adapted from FAO Forestry Paper No. 30.

TABLE 7
AVERAGE ANNUAL PRODUCTION OF SAWLOGS AND VENEER LOGS PER HECTARE OF PRODUCTIVE CLOSED FOREST (1976-1979)
(in m^3/ha/year)(1)

Tropical region in	Closed broadleaved productive forest	Productive coniferous forests	Closed broadleaved and coniferous forests
Tropical America (23 countries)	0.04	0.62	0.06
Tropical Africa (37 countries)	0.09	0.26	0.10
Tropical Asia (15 countries)	0.38	0.49	0.39
All the 75 countries	0.18	0.58	0.14
Europe without the USSR (25 countries)	0.62	1.40	1.08

(1) FAO Paper No. 30

TABLE 8
ANNUAL RATES OF DEFORESTATION AND PLANTATION DURING 1981-1985
(in million hectares)(1)

Tropical region in	Annual rates of deforestation			Plantation	Plantation: deforestation ratio
	Tree formations				
	Closed	Open	All		
America	4.3	1.2	5.6	0.5	1:10.5
Africa	1.3	2.3	3.7	0.1	1:29
Asia	1.8	0.2	2.0	0.4	1:4.5
Total	7.5	3.8	11.3	1.1	1:10

(1) Adapted from FAO Paper No. 30

TABLE 9
FOREST AREA AND POPULATION IN THE TROPICAL REGIONS AND SUB-REGIONS IN 1980(1)

Sub-region/region	Total area (in million ha)	Tree cover %	Total population			Agricultural population	
			Total (in million ha)	Density/ha of tree area	Rate of annual growth 1975-1980 %	Total (in million ha)	Rate of annual growth 1975-1980 %
Central America and Mexico	247	27	92.6	1.38	3.31	36.6	1.31
CARICOM	25	79	4.4	0.22	1.54	0.9	-1.26
Other Caribbean	45	59	22.2	0.84	1.95	9.6	0.69
Tropical South Latin America	1362	57	202.6	0.26	2.84	73.2	0.81
TROPICAL AMERICA	1680	53	321.8	0.36	2.89	120.3	0.93
Northern savanna region	424	10	29.6	0.68	2.65	24.5	1.99
West Africa	212	26	113.8	2.04	3.19	64.9	1.81
Central Africa	533	63	48.0	0.14	2.60	35.1	1.88
E Africa & Madagascar	881	25	149.7	0.69	2.95	116.1	2.23
Tropical S Africa	140	36	1.8	0.04	2.81	1.2	1.68
TROPICAL AFRICA	2189	32	343.5	0.49	2.95	241.7	2.09
South Asia	449	15	895.4	13.45	2.46	580.4	1.57
Continental S-E Asia	119	40	83.0	1.74	2.71	54.2	1.84
Insular S-E Asia	255	58	216.8	1.47	2.55	119.4	1.22
Centrally planned tropical Asia	75	48	64.9	1.78	2.28	46.2	1.49
Papua New Guinea	46	83	3.0	0.08	2.54	2.5	2.08
TROPICAL ASIA	945	36	1263.2	3.75	2.43	802.8	1.53
Total 76 countries	4814	40	1928.5	1.00	2.63	1164.9	1.58

(1) From FAO Forestry Paper No. 30.

TABLE 10
ESTIMATES OF ANNUAL SUPPLY AND GROWING STOCK

Region/Country	Supply			Comments
	Softwood/ hardwood	1980 (million m^3)	2000 (million m^3)	
North America	-	-	-	Growing stock 38 billion m^3
Canada	S	168*	217*	" " 18 " "
	H	21*	21*	
USA	S	267*	317*	" " 20 " "
	H	88	142*	
Western Europe	-	300*	387*	" " 11.6 " " (in 2000)
				Increment 361 million m^3/yr
Japan	-	55*	58*	
Latin America	S	27.4	71.3	Growing stock 100 billion m^3
	H	32	62	3.5 million m^3 plantations (in 1980)
Brazil	S	5.7	32	
	H	24	-	
Chile	S	4.1	25	
Mexico	S	-	4.0	
Far East	S	5	23	
	H	102	169	Large resources
South of Sahara	S	6.3	13	
	H	34	57	Large resources
North Africa - Mid-East	-	9	17	
Oceania	S	14*	38*	Exports 6.6 million m^3 in 2000
	H	12	20	
Eastern Europe	S	-	55	
	H	-	36	Growing stock 3.9 billion m^3
				Increment 120 million m^3/yr (in 2000)
USSA	-	-	447	Growing stock 75 billion m^3
				Increment 575 million m^3/yr
China	-	-	-	Growing stock 4.6 to 7 billion m^3

* Including residuals

TIMBER ENGINEERING AND ITS APPLICATIONS IN DEVELOPING COUNTRIES

John G. Stokes[1/]

For many centuries wood was the structural material most widely used throughout the world, and it was used because it was available, was understood and it could be easily worked. Additionally, there were no options in many applications.

The onset of the Industrial Revolution in the developed world brought with it an increasing availability of wrought iron and later steel sections, and engineers were quick to devise effective ways of fastening these sections together.

Firstly bolts and then rivets enabled iron bridges and tall steel buildings to be safely built. The evolution of welding brought an even more effective and predictable fastening system which appealed to engineers and enabled the design process to move from empirical data to a precise and predictable engineering basis.

Likewise, reinforced concrete developed rapidly as a predictable material of construction to which similar methods of engineering design could be applied.

Not so for wood, however, and, whilst thousands of wooden bridges and buildings were erected, engineers tended to move away from wood as a structural material, using it in the main for temporary structures, formwork and in domestic houses of a permanent nature.

Why did this happen?

Firstly, wood behaviour is only predictable to a degree which will satisfy knowledgeable engineers when it is well sawn to a standard size, is free of such faults as would cause its strength to fall below agreed

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[1/] Vice-President, International Gang-Nail Systems Limited, Perth, Western Australia.

limits, is at or below a predetermined and agreed moisture content, is of a known species or an agreed group of species whose characteristics are known, and if not resistant to insect and fungal attack, has been treated to ensure an adequate structural life.

Wood has numerous virtues, many of which were well known to mediaeval timber engineers and their successors in the western world and to ancient craftsmen of Asia and the Americas.

Hence we have seen wood used as a structural material 'in the round', as poles, piles and beams, and even today excellent traditional houses can be seen in Borneo, Thailand, Laos, Cambodia, Polynesia and Micronesia, of which the main frame is based on poles or bamboos used in a most effective fashion. Likewise, some innovative architects in Australia, New Zealand and North America have produced and built houses based on treated softwood poles which are most elegant and attractive structures.

Pole barns are widely and effectively built and used on farms in North America and, to a lesser extent, elsewhere.

Wood can be readily worked. It can be sawn, split, hewn, adzed, nailed, dowelled, screwed, carved, drilled, routed, planed, shaped, sanded, bent, finger jointed, laminated, spliced and peeled.

It can be changed and reconstituted through chemical preservation or fire retarding, densified and resin impregnated.

Likewise, it can be exploded or abraded into its constituent fibres and then reconstituted as hardboard or chip board or paper.

It can be ground into explosive wood flour or mechanically converted into wood wool or chips or flakes which, in turn, can be rebuilt into panel products using glues or cement as a bonding agent.

From all of these elements a vast family of building materials, papers and cardboards are reconstituted.

Despite all of these virtues wood lost ground as a structural material, and a number of factors were involved.

Many ambitious wooden bridge structures failed during the 19th Century because of the lack of adequate fastening devices; the lack of clear understanding of certain engineering fundamentals particularly important in timber engineering and the lack of stress grading facilities.

These complicating factors were quickly taken care of in iron and steel sections which, within certain limits, did what they purported to do and hence were attractive to the engineering profession.

Likewise, reinforced concrete quickly showed itself to be reasonably predictable providing many criteria; some of them hard to achieve, were met.

With wood, the criteria outlined above have been met only in the last two decades and reliable, structurally stress graded predictable wood sections are now available today throughout the developed world.

Secondly, and regrettably, fastening systems for wood did not keep pace with those available for steel. No process developed for the welding of wood until something akin to this was invented in the late 1950s.

The first improved joint for wood was the TECO Split Ring Connector which was developed in the early part of the 20th Century and this was followed by the development of finger joints in the United States and Germany in the 1950s which revolutionised firstly the Glulam Industry and has now been used in the manufacturing of trusses both as members and as a means of jointing trusses.

Improved glues emerged in World War II to the extent that the successful Mosquito Fighter Bomber was designed as a glued wood structure and reliably achieved design strength and life. Whilst properly glued joints equate to welded joints, the technical problems of mass producing glued structural joints have not yet been conquered.

I refer to the concept of producing a custom truss using finger joints at the panel points, which is being done in parallel chord trusses for concrete formwork but has not been mastered for custom built house trusses of varying pitch and profile.

Glue laminated structures in wood became increasingly evident and accepted after World War II, made possible by the rapid improvement in glues and gluing techniques and improved techniques for drying wood to allowable moisture contents without significant distortion.

The not so favourable economies of 'Glu Lam' construction, however, in most countries outside the United States, has slowed the widespread use of glulam despite its predictability and aesthetic attractions.

In other words, Glulam in most other developed countries does not rival the widespread usage of Glulam beams in North America. Nevertheless, there has been an impressive expansion in the use of stock Glulam beams in Australia and New Zealand and in Europe where its high strength, predictability and aesthetic appeal are winning favour.

The CSIRO here in Australia has been a most significant contributor to the successful growth of the market for engineered timber products as has been the New South Wales Forestry Department's Division of Wood Technology in Sydney, and their work in this field is world renowned.

Just what is timber engineering?

Broadly speaking, I believe that most of us would be in agreement that timber engineering is that section of the field of wood technology comprising the research, design, fabrication and erection of wood structures whether the end use be a chair, a beam, a bridge or a roof structure.

It is becoming increasingly evident that today's timber engineer can no longer be solely a researcher or a designer or a production man in isolation because he lives and works in an environment where cost is a vital factor and alternative materials are constantly being developed.

Hence he must have technical knowledge and abilities plus a strong commercial outlook embracing the many constraints of the real world, which range from an in-depth understanding of his materials, to possessing a keen sense of quality consciousness consistent with the clear knowledge that his end product, be it a table or a wooden bridge or wall frame, must be slender, strong and economically affordable.

The latter point is of particular significance in the developing world.

Before moving into detailed aspects of my topic, I believe we should firstly look at the material itself and how it is produced.

In the presence of so many wood scientists and experts it would be presumptuous of me to more than refer to the area of forest technology, which has made enormous gains, nor will I touch on such subjects as to how genetically superior trees are now produced and harvested to produce more and better wood.

Suffice it to say that trees are grown either in plantations or through programmes of regeneration of natural forests and that today bigger and better yields of wood are achievable.

Virgin forests are rare and are now largely preserved as national parks whereas operational forests are largely planted or regenerated.

It is of interest to note that the tree itself is a structure in wood and hence a fine example of timber engineering!

Resilient and capable of resisting most storms and earthquakes, trees are the great survivors of this world, with living examples dating back before the times of most of our prophets, Christ, Buddha and Mahummad.

Within a species, trees vary depending upon genetic background, soil types, rainfall and location in which they are grown, and I well remember as a young man in the West Australian timber industry, how we used, from time to time, to receive orders for 60' or 19.7 metre long keels for pearling luggers.

The specification would read: - '12" x 8" x 60' ridge grown quarter sawn Jarrah, free of heart, bark and wane, the piece to be free of spring and bow.'

I hasten to add that this is a specification which could not be achieved today and which was difficult to achieve 35 years ago.

I mention this specification out of interest and because of my earlier reference to variation between trees of the one species and this specification, based on experience rather than upon research, showed that builders of wooden boats had observed that trees grown on exposed hills and ridges were more dense and hence stronger.

In timber engineering, we are not dealing with a homogenous material as steel appears to be, and as concrete is often thought to be, and herein lies one great and recent advance in timber engineering, namely successful development of mechanical stress grading of wood.

Later speakers will elaborate on what timber engineers have done to develop equipment to accurately mechanically grade wood on a strength/ stiffness basis.

What I would like to emphasize is that timber engineering became a reliable science when ways and means of consistently drying and then stress grading of wood were developed. These innovations, coupled with methods of achieving improved durability, all paved the way for the introduction of improved gluing and fastening techniques and hence a rebirth of timber engineering.

Let us now turn to your special area of interest - the developing countries.

I am not of the opinion that glued structural joints will be of significance in the developing countries in the next decade. I say this because my frequent visits to many of your countries indicate that, whereas certain advanced Companies and Government Organisations are sawing and drying large quantities of wood with consistent precision for export markets in particular, a majority are not, and until there is major investment in kiln capacity and the local manufacture of glues, the use of glues for structural purposes outside of the plywood and particle board industry will not be significant.

We have many other Timber Engineering developments in the developed world, few of which, in my view, have immediate application possibilities in the developing countries.

I refer to factory mass-produced plywood and Microlam 'I' beams which are an excellent product but are volume dependent and have not as yet been developed using tropical hardwoods as the base material.

Similar excellent 'I' beams are mass produced in Sweden using long fibred masonite as a web in conjunction with kiln dried softwood flanges.

Equipment has been developed in the United States and Sweden for continuous assembly and gluing of Truss Joists of this type, but I do not see this capital intensive volume-dependent engineered timber beam as having a potential outside of Europe and North America for more than a decade.

I see some possibilities in the truss field for perforated structural nail-on plates with hand applied nails hammered through the pre-punched holes in the plates, and I believe Messrs Tadich and Francis will refer to this method of structural jointing in later papers. These are generally referred to as 'Nail-on Plates'.

This is appropriate technology and is particularly applicable in remote areas where in the villages, Kampongs or Barrios, a limited number of trusses is needed and transport is difficult or out of the question.

The disadvantages of 'Nail-on Plates' are associated with an excessive area of steel being necessary, which is due to limitations on nail centres, increased slip also occurs due to the lack of fixity between the nail and the parent plate, and the frequent omission of nails by tired or careless workers, particularly towards the end of a gruelling day on the end of a hammer when concentration wavers and that elusive nail flies off into oblivion.

However, such connectors, properly used, are adequate for the provision of shelter, particularly where small spans are involved.

Better than the nail-on plate (because it is more difficult to err) is the Grasshopper Plate in which the teeth are hinged from the parent plate and struck home by hammer.

Developed originally in the United States, these have been improved for use in New Zealand and Australian softwoods and more recently vastly improved for use in tropical hardwoods.

The only disadvantage of these connectors is that they are factory produced and hence have to be transported from a producing centre to the point of usage.

This, however, must also be done with the steel for local production of perforated nail-on plates, and, additionally, because of the reduced centre distance between nails, less steel is used to make a grasshopper plate than to make a nail-on plate.

This is a critical issue because appropriate heavily galvanized structural steel is expensive and is generally imported in most developing nations.

More efficient again, the multi-nail spiked connector plate has achieved by far the greatest successes and has, in my view, the biggest potential for the structural jointing of wood in the developing nations.

Truss plants have been developed ranging from the labour intensive, cheap and most simple jig using a 'hand-rammer' for the application of the connectors through to mass production plants using a minimum of labour.

Trusses so made have numerous advantages over hand-made nailed, bolted or 'nail-on' type of trusses!

Slip is minimal when the load is applied, trusses are identical because of the production jigs utilized and performance can be guaranteed, and even where labour is in surplus and inexpensive, such trusses have a relative cost advantage because of joint efficiency and speed of production which cannot be ignored.

In addition, spiked metal connectors are very efficient with nails rigidly connected to the parent plate giving much less area of steel for the same loading.

Hence importation is minimized and where desirable and the volume warrants, a joint company within the developing Nations to produce the connectors is generally the correct solution.

Structures made from these connectors range from farm gates to heavy duty racks for storage of steel, timber, pipes and so on, through to roof trusses for agricultural, commercial and industrial buildings, and the latter is by far the biggest usage.

Stainless steel connectors are made for use in aggressive and in marine environments such as are encountered in plating works, fish cooperatives, acid plants, superphosphate and other fertilizer works, steam laundries and chemical plants.

Here the unbeatable combination of rust-free stainless steel, plus corrosion proof wood gives maintenance-free trusses of predictably high strength and long life.

Costs are all important in today's competitive world and recent studies in Malaysia have consistently shown that spiked metal connector plated trusses are 15% to 30% cheaper than similar bolted or hand-nailed trusses and it is for this reason that Malaysia's mass housing programmes utilize Gang-Nail trusses on a virtually exclusive basis.

Elsewhere similar mass usage is emerging in Eastern Bloc countries for agricultural buildings and, similarly in Mexico and South America, where we are experiencing increased usage in mass housing programmes, frequently using green or air dried wood, pressure treated if necessary.

In addition to the above, the splicing of long length tile battens, purlins, girts and rafters from short lengths is finding rapid acceptance as a means of reducing waste and increasing recovery, and, again this is done with the same spiked connectors, appropriately sized.

Another important usage of spiked connectors is in the prevention of splitting of heavy wood sections such as logs, piles, poles, bridge and veneer flitches, wharf timbers and railway sleepers.

Applied to the end grain, for instance, a spiked anti-splitting connector on each end of a sleeper has been shown to be the most effective and economic way of preventing splitting or repairing an already split sleeper after first closing up the crack with a portable press.

In conclusion, I would like to touch on the economics of the most commonly engineered timber structures in the developing world - namely the domestic roof.

If we use the situation in Malaysia as a case study and compare bolted timber trusses with Gang-Nail trusses of identical span and pitch using timber prices applicable in January 1983, we will see in Malaysia the following price comparison:

(1) Gang-Nail Trusses

Timber quantity = 47.09 ft^3

Assume 8% wastage

Therefore timber quantity including wastage = 50.86 ft^3
= 1.017 tonne

Treated timber at M$410/tonne

Timber cost = M$417.00
Gang-Nail plates cost = 187.00
Fabrication = 79.00
Cartage = 46.00
Crane = 35.00

Total cost of GN truss delivered to site and crane onto roof = $ 764.00

Labour to erect trusses + installation of ancillary timber
11.0 squares at 24.0/square = 264.00

Ancillary timber (assume wastage 15% on battens, 10% others)

Battens:
2" x 2" x 1100FR x 1.15 = 35CF = 0.70 ton at $380 = 267.00

Wall plates:
4" x 4" x 120FR x 1.10 = 7.5CF = 0.15 ton at $410 = 62.00

Fascia board:
10" x 1" x 102FR x 1.10 = 7.8CF = 0.16 ton at $540 = 85.00

Mid-web tie:
3" x 2" x 20FR x 1.10 = 1.0CF = 0.02 ton at $410 = 9.00

423.00

Total cost of Gang-Nail truss roof: M$1451.00

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(2) Bolted Trusses

Timber quantity = 95.82 ft^3

Assume 15% wastage

Therefore timber quantity including wastage = 110.19 ft^3
= 2.20 tonne

Treated timber at M$410/tonne

Timber cost = $ 904.00

Bolts and nuts, minimum 211 sets, allowing for wastage
Number of sets required = 250, cost at $0.70/set

Bolt and nut sets = 175.00

Labour to fabricate and erect trusses and installation of ancillary timber

11.00 squares at 35.0/square = 385.00

Ancillary timber (assume wastage 15% on battens, 10% others)

Battens:
2" x 1" x 1100FR x 1.15 = 17.6CF = 0.35 ton at $350 = 123.00
Wall plates:
4" x 2" x 120FR x 1.10 = 7.5CF = 0.15 ton at $410 = 62.00
Fascia board:
10" x 1" x 102FR x 1.10 = 7.8CF = 0.16 ton at $540 = 85.00
Ridge board:
6" x 2" x 10FR x 1.10 = 1.0CF = 0.02 ton at $470 = 10.00

280.00

Total cost of conventional roof M$1744.00

SUMMARY

1. Total cost of conventional roof per unit = $1744
2. Total cost of Gang-Nail truss roof per unit = $1451

Difference = $ 293

Saving achieved in using Gang-Nail system = 17%

Note A: For purposes of comparison, profit has been excluded from both alternatives, i.e. totals are cost values.

In closing, I have great pleasure in being your Keynote Speaker and I would be most happy to discuss any aspect of matters touched upon within my paper during the course of this Workshop.

WOOD, THE MATERIAL

W. E. Hillis[1]

1. INTRODUCTION

Wood unlike most other building materials is a renewable material grown under a variety of conditions and obtained from a large number of species. As will be explained wood is both chemically and physically heterogeneous but with understanding it can be used at least equally as successfully as other materials in engineering structures.

In a broad description, woods are from two types of trees: the trees carrying needle-shaped leaves such as the conifers which yield the so-called softwoods. Their wood structure is simple and containing about 90% or more fibres with the remainder being the rays and a few other cell types. There are very large numbers of broad-leaved trees which yield the so-called hardwoods. They are not always harder than the softwoods but hardwoods always contain a number of cell types notably the vessels or pores which have diameters larger than those of the fibres.

2. THE TREE

The tree consists of three main parts: roots, stem or trunk and leaves. The roots anchor the tree in the ground and take in water and mineral salts from the soil. The trunk conducts these solutions from the roots to the leaves; it stores food materials and provides mechanical support to the branches and leaves. The leaves absorb carbon dioxide and with the energy obtained from sunlight synthesize the substances required for maintenance of growth.

The trunk is the important part of the tree as far as the wood-user is concerned. The outer covering of the trunk, the bark, protects the wood from extremes of temperature, fire and mechanical injury and the inner layers of the bark translocate the food synthesized in the leaves to the regions of growth and of storage.

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[1] An officer of CSIRO, Division of Chemical and Wood Technology, Melbourne, Australia.

A thin layer of tissue, the cambium, is situated between the bark and the wood of the tree and forms a sheath covering the trunk and the branches. When the cambium is growing during the spring and summer or during the wet months, wood is produced on the inside of the layer and bark towards the outside. The wood of trees grown under seasonal conditions consists of a series of concentric layers of tissue referred to as growth rings and each layer comprises the wood produced by the cambium in a season of growth. A new ring of wood is added each full season causing an increase in girth. In temperate regions, and some tropical countries, the alternation in each year of a growth season, and a resting period, results in the growth rings being annual rings although sometimes interruptions to growth causes two or more false rings to be produced within one growth season.

The outer growth layers of the stem, known as sapwood, store food and conduct sap to the leaves. The sapwood is from half a centimetre to several centimetres wide, depending on species, age of tree and forestry practices. Freshly cut sapwood is ligher in colour than the wood towards the pith or centre of the tree, it is less durable and usually contains more water than the heartwood. It has similar strength properties to the remaining wood.

3. GROWTH OF THE TREE

3.1 Growth in Height

The increase in the height of a tree or in the length of a branch is due to the division and growth of special cells at the tip. Elongation of the tip is the only lengthwise growth that occurs in the tree. In the young tree, vertical growth is rapid but as the tree matures, the growth continues to slow down appreciably.

A short way back from the growing tip the cells on the outside form the cambium layer whereas the inner cells form the pith which extends through the centre of the stem and branches. The pith is of small diameter and when noticeable it usually consists of brown, spongy material.

3.2 Growth in Girth

As the tree grows in height there is a corresponding growth in girth due to the division and growth of cells of the cambium layer. The soft thin-walled cells of this fine layer extend around the stem from the roots to within a short distance of the growing tip. By division they give rise to cells which form the woody cylinder of the tree. As time proceeds, the stem or trunk increases in girth by the addition of new cells on the outside of those already formed.

The growth in height is a function of the special cells located at the tip whereas the growth in girth is a function of the cambium layer and does not influence the growth in height.

Cone-shaped sheaths are formed as the tree increases in height and girth. A board cut parallel to the bark along the length of the tree will contain wood of the same age throughout its length.

4. THE CELL WALL OF WOOD FIBRES

The cell wall is made up of a twisted skein of cellulose molecules bunched into elementary fibrils and ordered into microfibrils which are embedded in a matrix of hemicelluloses and lignins.

4.1 Elementary Fibrils

There is evidence that each elementary fibril consists of 40 cellulose molecules held in close association by hydrogen bonding. The cross-sectional dimensions are about 3.5 nm by a multiple of 3.5 or 4.0 nm (3.5 or 4.0 x 10^{-9} m). In the elementary fibril, ordered crystalline regions of 300 nm length are separated by "amorphous" regions where the molecules become less orderly. It is at these amorphous regions where water may move between the elementary fibrils of cellulose molecules and where degradation by acids or by heat can occur. Processes such as shrinkage and swelling occur preferentially at these places.

4.2 The Nature of Microfibrils

The cellulose elementary fibrils of about 3.5 nm width are embedded in a matrix of hemicelluloses and lignins. Different theories exist concerning the arrangements of the components of the fibre cell wall and the situation can be exemplified by the proposal of Fengel. In this model a cellulose elementary fibril is surrounded by a few layers of hemicelluloses which have considerably less crystallinity, lower molecular sizes and degree of orientation than cellulose. The elementary fibrils are arranged in groups of 16, then into microfibrils containing a total of 64 elementary fibrils which are surrounded by hemicelluloses and lignin.

4.3 Arrangement of Microfibrils in the Cell Wall

Wood cell walls are thus chemically heterogenous, being composed of several different substances, and also physically heterogenous as they are built up of layers. The wood cell wall consists of three morphologically distinct layers: the middle lamella, the primary wall and the secondary wall. The thin middle lamella, which is an amorphous cellulose-free layer between the primary walls of adjacent cells, becomes heavily encrusted with lignin. During the growth of the cell the thin primary wall is a flexible structure composed largely of cellulose but towards the end of growth it becomes considerably lignified. Towards the end of the growing phase the thick secondary wall begins to form in 2 or 3 layers in a process which continues after cell growth has stopped.

In the primary wall (about 0.06 x 10^{-6} m thick) the microfibrils are arranged in a multinet structure, and towards the end of the growth phase they tend to be oriented increasingly in a longitudinal direction.

The secondary cell wall in wood fibres consists of microscopically distinct outer (S1), middle (S2) and inner (S3) layers. The middle layer is by far the thickest being 1.5-8 x 10^{-6} m with the other two about 0.1 x 10^{-6} m thick. The microfibrils in all layers are helically arranged but the pitch of the helices differs from layer to layer. In the S1 layer there are two or more helices of microfibrils which make large angles with the cell axis. The concentric lamellae of microfibrils arranged in helices in the S2 layer make a small angle with the axis. The inner S3 layer, which is sometimes absent, has a shallow pitched helical organisation with several lamella.

Wood cellulose has a density of about 1.55, the amorphous hemicelluloses 1.50, and lignin a density of only 1.33.

4.4 Porosity of Cell Wall

The framework of microfibrils in the cell wall in sapwood encompasses "free" space containing water and other materials. The hydrated S2 layer of the tracheid cell walls in *Pinus resinosa* contains 25% free space. The water in the capillaries of the wet walls of other woods has a volume of more than 40% (on a dry wood basis) with about half the water being in the free state. The free space in wet cell walls is in capillaries having cross sections from 16-60 x 10^{-10} m. Consequently, molecules of significant size can enter and act as fillers or modify to a considerable extent some properties such as stability and durability. A dimensionally stable wood such as redwood *Sequoia sempervirens* contains up to three-quarters of its extractives in the cell wall.

The small voids in the dry cell wall affect its packing density which is a more relevant indicator of the rate of penetration than is density. Packing density is higher in high density woods than in low density woods and higher in late and mature wood than in early and juvenile wood.

4.5 Distribution of Constituents in the Cell Wall

Although the concentration of lignin in the middle lamella and primary wall can be over 50% by mass, only 20-30% of the total lignin is found there; the remainder is in the much thicker secondary walls where it is present in amounts of 20-25%.

5. GROWTH RINGS

A new layer of wood is formed during each growing season between the bark and the stem of trees over the entire length of stem. The demarcation of these growth layers or growth rings results from differences in temperature, moisture availability, the growing and non-growing seasons and also in tree species. In most cases growth rings are formed annually. In tropical and sub-tropical regions, the growth rings can be indistinct. In dry regions with relatively high temperatures and intermittent rainfall several rings can be formed annually.

Growth rings are usually distinct due to differences in the wood produced early in the growing season (i.e. earlywood or springwood) as opposed to that formed late in the growing season (latewood or summerwood). Earlywood has the thinnest cell walls and large lumens whereas latewood with its small lumens and thick walls may appear as a dark zone. There are variations in the contrast between earlywood and latewood, the relative amounts of them and the abruptness in which earlywood stops forming.

These variations depend on the species, the differences in thickness of the cell wall, and the age of the tree when the growth ring was formed.

Dry latewood has a higher specific gravity than dry uncollapsed earlywood. However, in undried sapwood, the earlywood contains large volumes of water sometimes up to 4 or more times greater than that in the latewood due to the large lumens in the earlywood.

Some fast-growing species, such as Anthocephalus spp., produce high volumes of wood but contain large proportions of cells with thin walls and large lumens which, when occurring in sapwood, are filled with water.

6. SOFTWOODS AND HARDWOODS

6.1 Description

The two major groups of trees - softwoods (conifers, gymnosperms) and hardwoods (angiosperms) - are distinguished by the presence or absence of a cover on the seed. Whereas there are only about 40 genera and 600 species of softwoods there are thousands of genera of hardwoods with widely differing anatomical structures. The average oven-dry specific gravity of softwoods is about 0.36 with a range of 0.25-0.60 compared with 0.50 and a range of below 0.30 to above 0.80 for hardwoods. Much of the wood available globally is from hardwood species.

6.2 Major Anatomical Differences between Softwoods and Hardwoods

The fibre is the major single structural element in wood. In softwoods, fibres serve also as the major translocation route for sap, and are inter-connected by openings known as bordered pits and are defined as tracheids. In hardwoods the fibre elements are usually thick-walled with simple and slit-like pits. The characteristics of these elements vary within the tree, the species and between species. Tracheids and fibres are considerably longer than they are wide, with ratios of sometimes 100 to 1. The length of tracheids range from about 3-4 mm and usually in commercial softwoods. The diameters range from about 20 to 80 x 10^{-6} m. The length of hardwood fibres ranges from about 0.5 to 1.8 mm and the diameter from about 10-25 x 10^{-6} m.

The major anatomical difference between softwoods and hardwoods is the presence of vessels (or pores) in the latter. The vessels, through which the sap is conducted in the living tree, have a very wide range of size, shape and arrangement. In ring-porous hardwoods the vessels in the earlywood portion of a growth ring have different sizes from those in the latewood. In diffuse-porous woods the vessels have the same size at all locations in the ring. The length of the vessel elements varies from 0.18 to 1.3 mm and the width from 20 to over 250 x 10^{-6} m. For a number of hardwoods the vessel diameter increases and vessel frequency decreases as the distance from the pith increases. The frequency of vessels per mm^2 varies according to the species, the size of the vessels, the position in the growth ring, the distance from the pith and growth conditions. The walls of vessels are thin (about 3-4 x 10^{-6} m).

6.3 Parenchyma

On the cross-sections of woody stems, the ray parenchyma extend as lines from the pith outwards to the cambium and are seen as lines between the fibres. In conifers and some hardwoods, the rays are 1-2 cells wide and 10-20 cells high. In other hardwoods the rays can be up to about 30 cells wide, sometimes hundreds of cells high and are tapered on their upper and lower edges.

Vertical parenchyma are also thin-walled cells and are interspersed between the fibres and arranged diffusely or surround the vessels in various patterns. In contrast to the fibres, the ray and vertical parenchyma remain alive across the sapwood zone. In the sapwood they translocate or store primary metabolites such as starch or fats; in the heartwood they frequently contain large amounts of extractives.

6.4 Resin Canals

Coniferous wood contains resin canals about the same size as some vessels. They exist as anastomosing networks surrounded by epithelial cells which form and exude resin into the canal. Frequently, the resin is under pressure so that when the canals are cut in the living tree the resin exudes.

6.5 Pits and Tyloses

When the pits, or openings in the cell wall, between the ray parenchyma and vessels are more than 10×10^{-6} m diameter, the parenchyma can form thin-walled, balloon-like extrusions - the tyloses - into the vessels. When the pit diameters are smaller the rays secrete extractives. These changes occur when heartwood is formed or when sapwood is injured. In conifers the bordered pits also aspirate or close during the transition of sapwood to heartwood. All these changes hinder the movement of fluids either into or out of the wood.

6.6 Proportion of Non-fibrous Elements

Whereas the proportion by volume of tracheids in conifers is usually over 90%, the proportion of fibres to the thin-walled elements in hardwoods is much lower (Table 1). The proportion of the latter affects the water content and the density of the material.

TABLE 1

Proportion of tissue elements in various woods

Percentage of total volume

Species*	Longitudinal fibres/tracheids	Parenchyma		Vessels
		Ray	Axial	
Betula papyrifera	75.7	11.7	2.0	10.6
Erythrina vespertilio	16	80		4
Eucalyptus camaldulensis	58	25		17
Juglans nigra	48.7	16.8	13.5	21.0
Liquidamber styraciflua	26.6	18.3	0.2	54.9
Picea abies	94.1	5.9	-	-
Pinus strobus	93.0	6.0	-	-
Quercus rubra	41.3	15.9	23.4	19.5
Salix nigra	54.4	6.1	2.2	38.1
Ulmus americana	34.7	11.3	6.0	48.0

*Common names vary between countries

6.7 Chemistry

The cellulose content of both softwoods and hardwoods is normally in the range of 42 ± 2% (on extractives-free basis). The hemicelluloses and lignin are found in complementary proportions and the woods with a high lignin content have a low hemicelluloses content. Generally, hardwoods contain less (16-24%) lignin than softwoods (24-33%).

7. WOOD FORMED UNDER ABNORMAL CONDITIONS

Responses to abnormal growing conditions result in reaction wood with ultrastructures markedly different from those of normal wood. Reaction wood is frequently formed in leaning trees and bent stems. Because of the low density of juvenile wood in young trees and the flexible nature of fast-grown trees under windy conditions, there is frequently a higher proportion of reaction wood in the central portions of these stems when compared with the outer layers of mature trees. In addition, stressed wood can be formed along the periphery of trees, particularly hardwood trees. This results when the crown seeks the optimum opening in the forest canopy so that the tree leans in a certain direction.

Leaning trees and branches that are transversely eccentric in outline often contain reaction wood in the regions of accelerated growth. In softwoods this is found in the underneath side of the trunk in the form of compression wood whereas in hardwoods it is in the upper side and is known as tension wood.

Stressed wood, and particularly reaction wood, has inferior properties for conversion into, or for use as, solid wood products.

7.1 Descriptions of Reaction Wood

7.1.1 Compression wood

This wood is readily detected in freshly-cut log cross sections. Its color is generally much darker than the color of normal wood of the same species. Pronounced compression wood can occur over large areas and contain a number of characteristic anatomical features. Compared with normal wood, compression wood contains shorter fibres with thicker walls, and a greater proportion of latewood in growth rings; its microfibrillar angle is much larger than in normal wood.

Compression wood is harder, heavier and more brittle than normal wood. It has a lower impact strength than normal wood and should be excluded from scaffolding and ladder material. It shrinks and swells much more than normal wood in the longitudinal direction and less in the transverse direction. If there is more compression wood on one side than another warp will occur on drying.

7.1.2 Tension wood

Eccentricity of growth and wider growth rings are often indications of the presence of tension wood. It is often found in bands which, compared with neighbouring normal wood, are usually darker in color, harder and denser. The main anatomical features are fibres with a light-refractory, inner layer often termed the gelatinous layer. There is also a marked reduction in size and number of vessels, and a higher average wood density.

In most cases, the presence of tension wood is revealed by the extreme woolliness of sawn longitudinal surfaces of green timber. This feature can be extremely troublesome in sawing, because the fibrous mass may choke the saw cut and cause overheating of the saw. The woolliness of veneer surfaces is also indicative of its tendency to collapse on drying and the collapse is of the non-recoverable type. Shrinkage in the longitudinal direction is high, radially it is normal, but tangentially the shrinkage may be greater than normal. Its presence can cause twisting in boards on drying.

7.1.3 Wood formed under load stress

Peripheral growth stress can reach high levels in significant portions of the outer sapwood of hardwoods. The wood formed in those regions has an increased thickness of cell wall, a greater microfibrillar angle in the S2 layer and a higher intensity of lignification. The high peripheral stress results in high compressive stresses in the interior of the tree so that compression failures occur in the fibres and the wood becomes brittle ("brash"). High growth stress cause logs to split open when felled or sawn.

7.1.4 Brittle heart

This occurs in the central zone (not always symmetrically placed) and is characterised by wood of low strength and a brash fracture due to minute "compression failures" in the walls of some fibres. Its presence is due to the high peripheral growth stresses sometimes found in some hardwoods, or to forces such as severe winds, which are counterbalanced by a related compressive force in the interior of the tree. If these forces are sufficiently high and imposed on wood of low density so that the crushing strength is exceeded then compression failures occur in the fibre walls. The wood has low impact strength and can be detected by its easier sawing characteristics and broken or foggy fibres on the end-grain, sawn surfaces.

7.2 Chemistry

There is a general pattern for both hardwoods and softwoods in that the wood on the lower side of any cross- section of a leaning or sloping stem has a higher lignin content and a lower cellulose content. There are gradations in composition and properties between severe reaction wood and normal wood within the one tree.

7.2.1 Compression wood

This wood can have substantially higher lignin and hemicellulose contents and lower cellulose contents than those in comparable normal wood with. Because of the higher proportion of lignin, the cell wall density of compression wood is less than that of normal wood. On the other hand, because of the small proportion of earlywood and the thick tracheid walls, the gross density of compression wood is much higher and almost twice that of normal wood.

7.2.2 Tension wood

Tension wood contains higher percentages of cellulose and lower percentages of lignin and hemicellulose than normal wood.

8. SAPWOOD AND HEARTWOOD

8.1 Volume of Sapwood

Sapwood is the outer zone and the portion of the wood that, in the living tree, contains living cells and reserve material (e.g. starch). Fibres and tracheids die as soon as the lignification phase is completed. On the other hand, the parenchyma remain viable for many years or until heartwood is formed or the wood is damaged.

The amount of sapwood in a mature tree can vary considerably, occupying the whole tree or only the outermost growth rings which surrounds an approximately conical shaped central core of dead heartwood cells. Sapwood forms, in red oak (Quercus rubra), a band of constant width of 1 cm or 5-6 growth rings around the heartwood, in pines 15-50 growth rings, and, of varying widths, in eucalypts about 5 growth rings, in maple (Acer spp.) over 100 growth rings. The width of sapwood in a cross-section of a stem of a tree is not always uniform and the number of sapwood rings can be greater at the stump than higher in the tree. Also with some trees of mature or over-mature age the width of the sapwood, and particularly the number of growth rings in it, is much greater than in young trees of the same species.

The mechanical properties of sapwood and heartwood of similar density and moisture content are practically the same.

8.2 The Contents of Sapwood

Most sapwood tissues in the living tree are involved in the translocation or storage of sap. The free water content of sapwood is determined by the lumen area of the elements after allowing for stored metabolites. The water content of sapwood can be high and over 200% (on dry weight basis) in some cases, for softwood sapwood it is usually between 110-170%, whereas for hardwood sapwood it is between 60-110%. Usually, the water content is maintained across the sapwood but decreases abruptly at the heartwood periphery.

Starch, fatty acids or esters of fatty acids are formed exclusively in the parenchyma, where they are stored as reserve material in the sapwood for growth or for extractives formation at the heartwood periphery. The storage material in the sapwood makes it prone to fungal and insect attack, hence chemicial or preservation treatments are necessary to render sapwood durable. In general treated sapwood may be superior in durability to heartwood.

8.3 Heartwood

In most growing trees or shrubs the inner layers of the stem or branches cease to contain living cells and the reserve metabolic materials are no longer present. This heartwood zone contains higher, sometimes much higher, amounts of extractives than in the sapwood and their composition is usually different. The zone is generally dark with a color range between light yellow and dark brown. Once the zone begins to form it is spatially continuous.

Less moisture is usually found in heartwood than in sapwood, and the decrease at the transition zone can be abrupt and considerable, coinciding approximately with the change in color. This decrease in moisture content is characteristic of softwood species and most hardwoods. However, the heartwood can contain more moisture than the sapwood in some hardwoods species such as Populus (poplar), Ulmus (elm), and Eucalyptus and in some cases this may be due to the formation of wetwood. The moisture content in the heartwood of softwoods is usually between 33-95% whereas in hardwoods it is usually 60-100%.

Together with loss of water on heartwood formation, a marked aspiration or closing of the pits between tracheids restricts the transport of fluids. When heartwood is formed in many hardwoods, tyloses appear in the lumen of vessels. Aspiration of pits and tyloses formation also takes place in sapwood in response to wounding.

Extractives are responsible for the distinctive colour of heartwood and are present in the parenchyma, vessels and some other cells, but also in the cell wall of the tissues. Extractives can hinder the movement of aqueous fluids. The amount of extractives increases from the pith to heartwood periphery, and abruptly decreases in the sapwood. Large amounts can be present in the outer heartwood, e.g. over 30% of polyphenolic extractives in old eucalypts. Usually, fast-grown trees of the same species contain significantly lower amounts of extractives than do the slow-grown counterparts. The composition of extractives in the heartwood varies considerably and depends on the genus to which the tree belongs. Part of the inorganic constituents of wood is located in the cell wall but larger amounts are translocated from the heartwood during its formation. The total mineral content increases from unblemished to discolored wood and again to decayed wood. Potassium concentrations can increase 400-4000%, calcium significantly and other elements in a less pronounced manner. A number of organic extractives can, when present, convey durability to the heartwood.

As the extractives or extraneous components are largely formed in the lumen of cells they have little effect on strength.

The major classes of organic extractives in heartwood are:-

(1) Polyphenols which are present in all woods although in some cases the amount may be low. Some classes of polyphenols can affect adhesion with glues, others convey durability, some cause corrosion during sawing etc., some discolour on exposure to sunlight, or with iron, or they affect paint films and other surface coatings.

(2) Resins are present mainly in the softwoods and include terpenes, resin acids and sterols. They are water repellant and can affect application where that property is involved.

(3) Fats exist as free fatty acids and their esters usually in softwoods but also in hardwoods such as poplars abd birch.

(4) Tropolones. Members of the Cupressaceae such as western red cedar (Thuja plicata) and other cedars (e.g. Chamaecyparis spp.) are the only tree species containing extractives based on this seven carbon ring structure. They readily react with copper and iron and convey a high degree of durability.

9. JUVENILE WOOD

Natural stands and plantations of both pines and hardwoods are being harvested at increasingly younger ages, and, as well, greater use is being made of the formerly non-merchantable tops and branches. Also, there is the development and use of short-rotation, intensively grown crops of fast-growing species. These raw materials contain increasing amounts of reaction wood and juvenile wood.

The age of the cambium at the point of wood formation determines whether juvenile or mature wood is formed and the former extends outwards from the pith about 6 to 15 rings where it has gradually taken on the properties of mature wood. It comprises the major portion of the wood formed in the first 20 years of growth at a particular level in the tree. Juvenile wood also contains a high proportion of earlywood and with increasing distance from the pith the fibre length, density and cell wall thickness increase steeply in the first few years and more slowly in the mature wood. When present spiral grain shows its maximum angle of inclination in the juvenile wood zone.

The moisture content varies widely with tree age and with location of the sample in the tree. The considerable drop of moisture content with age is due to an increase in density and to the presence of heartwood. The amount of extractives is lower in juvenile wood.

There are different interpretations of the terms juvenile wood, core wood, heart-in material. Juvenile wood is an inner core of wood surrounding the pith in which the cells are smaller and/or less structurally developed than those of the outer layers. The characteristics mentioned above are genetically inherited and perhaps modified by growth rate. In addition this clear wood may contain varying amounts of knots and branch stubs as influenced by silvicultural practices, irregular grain around the knots, reaction wood and wandering pith. This central zone of core wood can be of larger diameter than juvenile wood and the material cut from it may not contain the pith. Heart-in material is taken from the core wood and contains the pith and associated defective wood. The pith consists chiefly of parenchyma or soft tissue which reduces strength and wearing properties and appearance values. Usually its actual volume is insignificant but the pith can be particularly eccentric and affect the yield and quality of sawn wood.

10. IRREGULAR FEATURES

10.1 Knots

Various types of knots affect the quality of wood in different ways, and knots are often rejected. The knots of conifers become highly resinified whereas with hardwoods the branch stubs are not filled with extractives so that an entry point for insects and fungi is provided, leading to widespread discoloration and decay.

10.2 Wetwood

In freshly cut stems of some species, the small or large zones of wetwood (when present) are usually recognized by a darker or wetter appearance. They contain more water than the sapwood zone, and sometimes a gas, can be present. The pH and density are higher than those of the surrounding tissues, and the occurence of mineral stains or deposits, often of calcium carbonate, are frequently greater. The presence of wetwood causes problems during drying and penetration.

10.3 Discolored and Decayed Woods

Some types of discolored woods can be confused with heartwood because of their location and color. They are, however, part of a sequence of damage to the living tree which proceeds eventually to decayed wood. The zones are irregular in shape, color intensity and location within the stem; sometimes they occur as colored tubes within the stem. Often they occur longitudinally for a short distance as zones on one side of the tree.

10.4 Resinified Wood and Exudates

Cambial injury of many trees, particularly during the growing season, can result in the formation of organic materials which are confined to cavities - the veins or pockets - in the wood or which exude onto the bark of the tree. The size of the cavity and the amount and composition of the exudate depends on the nature of species and its conditions of growth. Conifers exude resins of the terpenoid type, eucalypts exude kino composed of polyphenols, the Prunus, Acacia etc. genera yield carbohydrate gums. Pockets reduce strength but veins have much less effect.

10.5 Spiral Grain and Interlocked Grain

Spiral grain or inclined grain is an arrangement in which fibres or other longitudinal elements take a spiral course about the axis of the tree. Spiral grain can be severe in the juvenile wood of softwoods. It is low at the pith but reaches a maximum usually around five growth rings from the pith and decreases usually to a straight-grained condition in mature wood. A slope of grain of 6° can reduce bending strength by up to 25%. Spiral grain causes twist in boards on drying unless high temperature drying under restraint is used.

Interlocked grain is found in hardwoods when the wood is difficult to split and when it does split a corrugated radial surface is left. It causes distortion when veneer is dried.

11. THE BEHAVIOUR OF WOOD UNDER LOAD

Studies of the behaviour of isolated, single fibres of wood under load have been confined to tensile loading because of the experimental difficulties involved in applying and measuring loads and deformations in specimens of very small dimensions. The large amount of work done on single fibres in tension and also on thin slivers of wood containing bands of fibres have established several interesting patterns of behaviour.

The tensile strength and modulus of elasticity of latewood fibres may be as much as three times the respective values for adjacent earlywood fibres and further, the strains at failure in both types of fibre appear to be similar in magnitude. The existence of constant strain at failure in whole wood in tension has also been observed in tests on a large number of species and lends support to a limiting strain concept. The tensile properties of single fibres are superior to those for whole wood and it is considered that the differences may be due to the presence of medullary rays, other cell types, imperfect alignment of fibres and local variations in density, in whole wood. Further the transfer of stress from cell to cell in whole wood is through shear in the middle lamella. The properties of the single fibre appear to be influenced by the angle of orientation of the microfibrils in the thick S_2 layer of the secondary wall of the fibre. The smaller the angle with respect to the longitudinal axis the greater the tensile strength of individual fibres. In tension parallel to the fibres in whole wood consisting only of latewood, bundles of fibres appear to pull out from among others which suggests that failure occurs in the region of the middle lamellae or the primary walls of the cells. In earlywood, failure appears to occur across the cell walls. In tension perpendicular to the grain, failure occurs either by the fibre breaking into two pieces along the length and exposing the lumen or by separation at the inside of the primary wall leaving the remainder of the fibre intact.

In compression parallel to the fibres in whole wood, lines of buckling appear on the tangential face at an angle of about 60° to the longitudinal axis and on the radial face at about 90°, i.e. parallel to the medullary rays. The departure of the buckling lines from an angle of 45°, the angle of maximum shear, is due to the anisotropy of wood. Slip planes or compression crinkles appear to develop within the cell wall and buckling of cells, together with separation near medullary rays, also occurs. In compression perpendicular to the fibres the cells distort sideways and squash inwards towards the lumen eventually separating at the outer boundary of the S_2 layer.

Whole wood may be represented in a simple form by a model consisting of a series of long, parallel, hollow, thin-walled tubes cemented together. Small groups of thin-walled tubes may also be arranged horizontally (radially) to represent medullary rays. Under the action of longitudinal tensile forces the system would be relatively strong, whereas in longitudinal compression the system would be weaker because of the tendency to buckling of the long columns, particularly with initial curvature in the vicinity of the rays. In lateral tension and compression, the strength of the thin-walled tubes would be lower than coresponding values in the longitudinal direction. Shear properties longitudinal to the fibres would also be low.

12. IMPORTANT PROPERTIES OTHER THAN STRENGTH

12.1 Density

Because of its link with practically all of the mechanical properties of wood, including those of structural importance, density must be rated as one of the most important of the non-structural properties of wood. However, there are some tropically grown timbers which may have a satisfactory density but consist of a small proportion of thick-walled high density fibres and a large proportion of thin-walled, large-diameter vessels, parenchyma, etc. These woods would fail more rapidly under load than woods with the same density, but containing a large proportion of fibres with walls of medium thickness.

Except in special circumstances, the self-weight of a timber structure is seldom a serious design consideration. In cases where self-weight is important, it should be noted that, in general, timbers of low density are more efficient on a strength/weight basis than those of high density, particularly for beams and columns. The obviously much higher strength/weight ratio of dry timber, as compared to that for green timber, should not be overlooked.

The competitive use of timber as a material of construction depends on the effective use of wood's outstandingly high flexural rigidity per unit mass. This property can be capitalized in the design of relatively large yet comaratively lightly loaded structures such as single storey buildings, all kinds of roof systems, towers, silos, bridges, and curtain walls.

12.2 Shrinkage

From the time it is cut from the tree, wood exposed to normal atmospheric conditions dries and shrinks. The loss of dimension tangential to the growth ring is, particulary in hardwoods, usually quite significant and is about twice that in the radial direction.

In the first stages shrinkage along the grain, except when abnormal wood such as compression wood is present, is usually small and of little or no practical significance. Generally, changes in dimensions of softwood timbers on drying are not as great as those of hardwoods although there are some of these of high density, wandoo for example, which exhibit a comparatively small shrinkage.

As the green timber dries below the so-called fibre saturation point (at approximately 25% to 30% moisture content) the normal shrinkage is more or less linear with moisture content change.

In a number of hardwoods, normal shrinkage can be enhanced by an abnormal change in dimensions called "collapse" which occurs when the moisture content of the timber is above the fibre saturation point. The phenomenon results from a collapse of the thinner walled fibres during the early stages of drying. It manifests itself macroscopically as an excessive shrinkage of the cross-section with a corresponding increase in apparent density. The surfaces of the timber are slighty to heavily corrugated depending on the severity of the collapse and internal checking can occur.

Hardwoods dried for joinery and similar uses are usually given a steaming or reconditioning treatment after drying. This has the effect of removing most of the collapse unless tension wood was present and restoring the timber to the cross-section and density it would have had if only normal shrinkage had occurred

Because shrinkage is a normal characteristic of wood, special consideration is required in the selection and use of timber in structures. Due to the gross anisotropy of shrinkage, timber containing severely distorted grain or sloping grain may warp badly on drying from the green to the air-dry condition. Green timber in a joint containing two or more fasteners secured in such a way as to offer restraint to the normal shrinkage of the wood will probably split as it dries. Most of the technical aspects of the working of wood, i.e. its shrinkage and swelling with change of moisture content, are fairly well understood and suitable design and construction procedures have been developed to obviate the problems that might otherwise arise if inadequate attention were to be paid to this particular wood characteristic.

Investigation has shown that for most structural grades of timber, the ultimate load-carrying capacity of individual members increases as the members dry from the green condition in spite of the loss of cross-section due to the shrinkage. For large sizes and low grades of timber there may be little or no significant increase in strength on drying due to the development of large splits and checks. The stiffness of hardwood members not subject to collapse increases on average by about 5% on drying from the green to the air-dry state, a change which for structural purposes is not considered of practical significance.

Although air-dry timber responds to changes in relative humidity by shrinkage and swelling, these small dimensional changes are seldom of structural importance; large sections are far less sensitive than small sections to changes in ambient conditions. Nevertheless it is desirable and, in extreme cases, essential, that timber in prefabricated structures, particularly if glued joints are involved, be conditioned before fabrication to the equilibrium moisture content for that timber in the area in which the structure is to be finally erected.

12.3 Thermal Properties

The thermal expansion of timber along the grain is only about one-tenth to one-third that of other structural materials, including glass, and so need be considered only in relation to differential effects when used with them. Thermal expansion across the grain is, in general, larger than along the grain. In most cases in practice, the shrinkage and swelling with moisture change which often accompany temperature changes overshadow thermal expansion.

12.4 Corrosion Resistance

Wood offers considerable resistance to attack by a wide variety of chemicals, including organic materials, hot or cold solutions of acid or neutral salts, and dilute acids. Direct contact with caustic soda, however, should be avoided. Strong acids and alkalis will destroy wood in time but the action is not rapid. Attack by chemicals on wood rarely releases products harmful to an industrial process. Consequently wood is superior to many other construction materials for certain industrial buildings.

Wood resists exposure to atmospheric pollution and to sea air, so is often better suited for many constructional uses near the coast. Timbers in roof trusses, beams and other structural members may be attacked by corrosive vapour, but the hazard is generally much less than with metals. Chemical attack in timber tends to be limited in depth and conservative design practice when hazardous conditions exist will normally ensure an economic life for the structure.

12.5 Electrical Resistance

Because its electrical resistance is high, wood is particularly suitable for such uses as poles and cross-arms for high voltage power lines. Its electrical resistance also varies with moisture content providing the timber is at least partly dry, and consequently it has been possible to develop electrical meters by which the moisture content of the timber may be readily determined by measuring the electrical resistance. The effect varies with species, so that special calibration factors are needed for each species.

12.6 Vibration Characteristics

Wood has excellent damping characteristics, its specific damping capacity being 0.06 compared to a value of 0.003 for steel. Timber floors exhibit much less vibration than floors with metal joists, and consequently give a feeling of greater comfort during movement across the floor for a given deflection under load. The comparative "softness" of wooden floors has been demonstrated to cause less muscle strain in walking than does a concrete floor.

12.7 Fire Resistance

Timber is a very poor conductor of heat, and although the outside surface of a timber member may be burning in a fire, the temperature only a small fraction of an inch below the depth of the charcoal being produced is at a relatively low temperature and the strength of the residual part of the member is retained. In general, the denser the timber, the longer it takes to ignite and the slower it burns.

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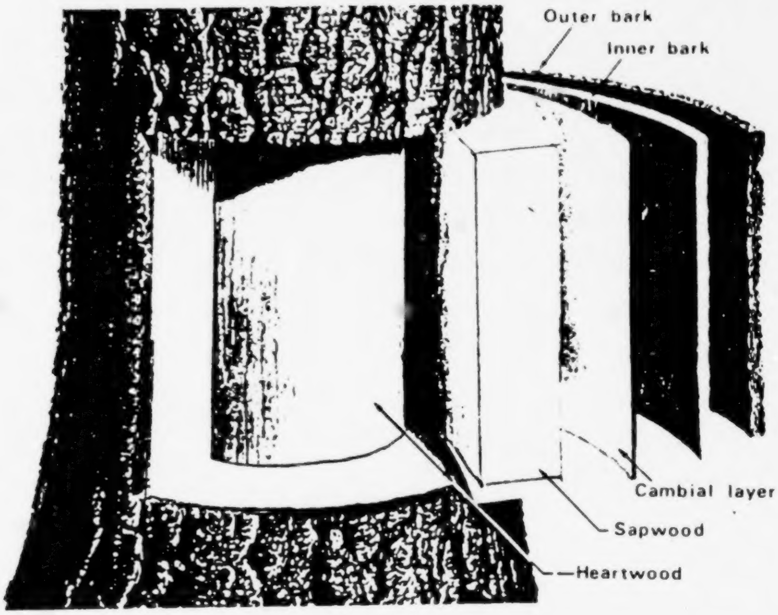
Outer bark
Inner bark
Cambial layer
Sapwood
Heartwood

Figure 1. Generalized structure of a tree showing orientation of major tissues including outer bark, inner bark, cambium, sapwood and heartwood (courtesy of St. Regis Paper Co.).

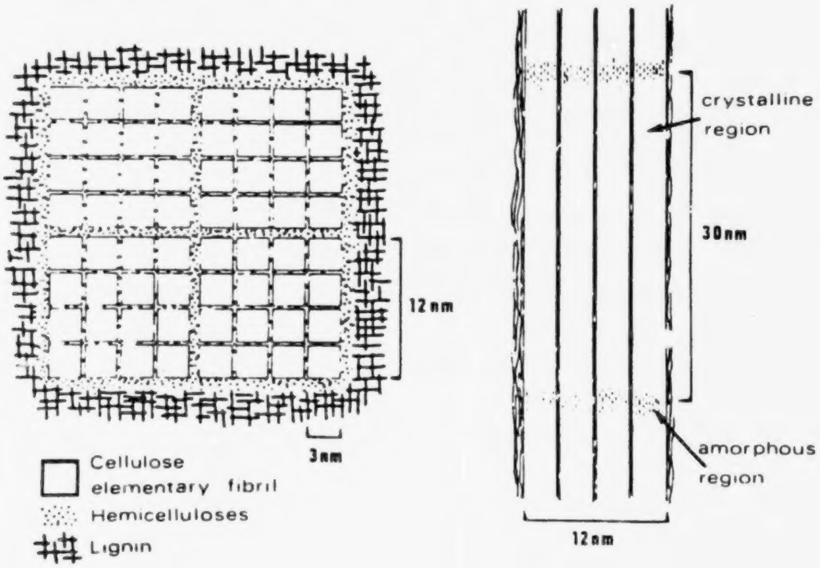
12nm
3nm
Cellulose elementary fibril
Hemicelluloses
Lignin
crystalline region
30nm
amorphous region
12nm

Figure 2. Model of the ultrastructural organization of a microfibril in wood; cross section on the left, longitudinal section on the right (after Fengel).

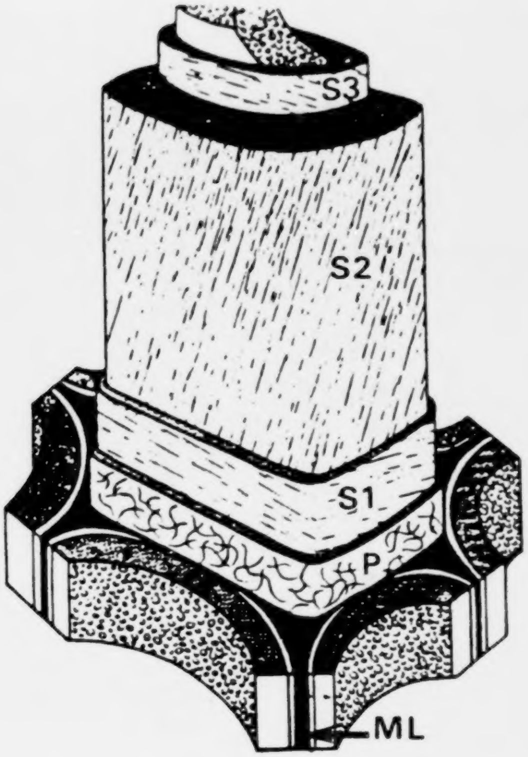

Figure 3. The ultrastructure of the wood cell wall (ML = middle lamella; P = primary wall; S1, S2 and S3 = layers of secondary wall; after Coté)

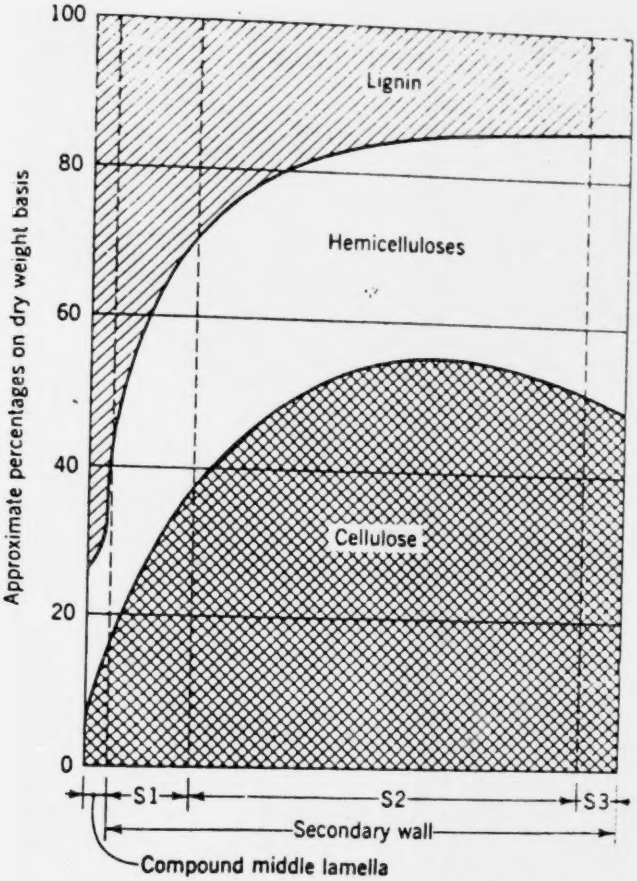

Figure 4. Distribution of the principal chemical constituents within the various layers of the cell wall in conifers (from Panshin, A. J. and de Zeeuw, C. 1980. "Textbook of Wood Technology". McGraw-Hill Book Co.).

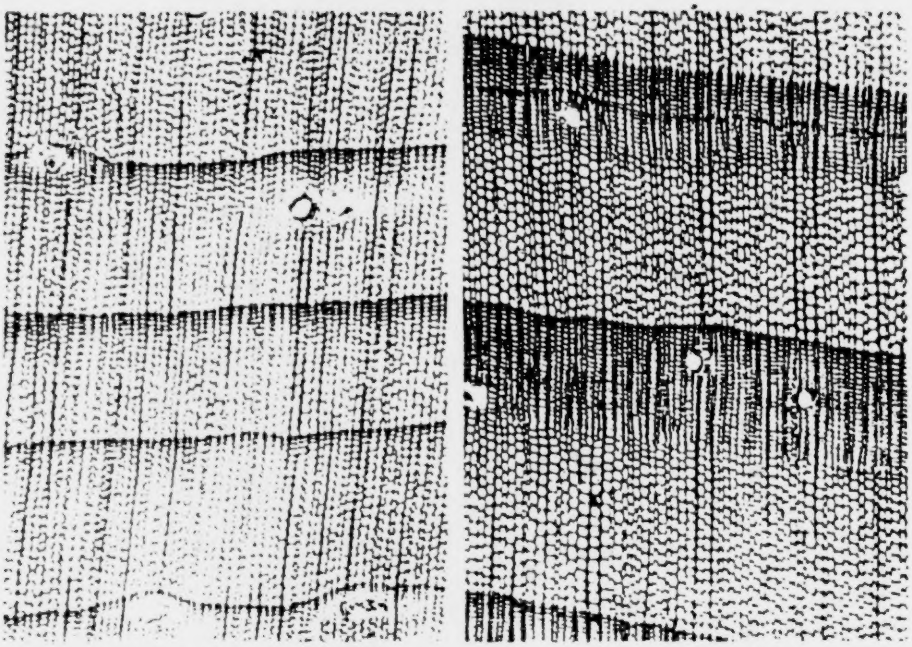

Figure 5. Variations in transition from earlywood to latewood in *Pinus* spp. White pine (*P. strobus*, left) and Loblolly pine (*P. taeda*, right) (about x 30). Note large diameter, vertical resin canal.

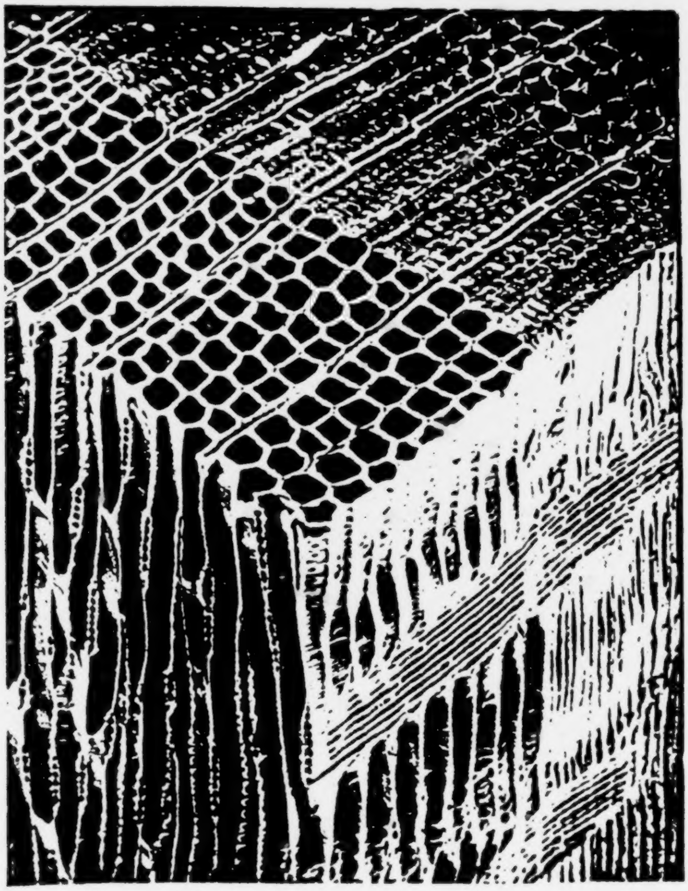

Figure 6. A softwood Douglas-fir (Pseudotsuga Menziesii) as viewed with the scanning electron microscope (about x 80), showing earlywood and latewood tracheids and rays (courtesy of W. A. Coté).

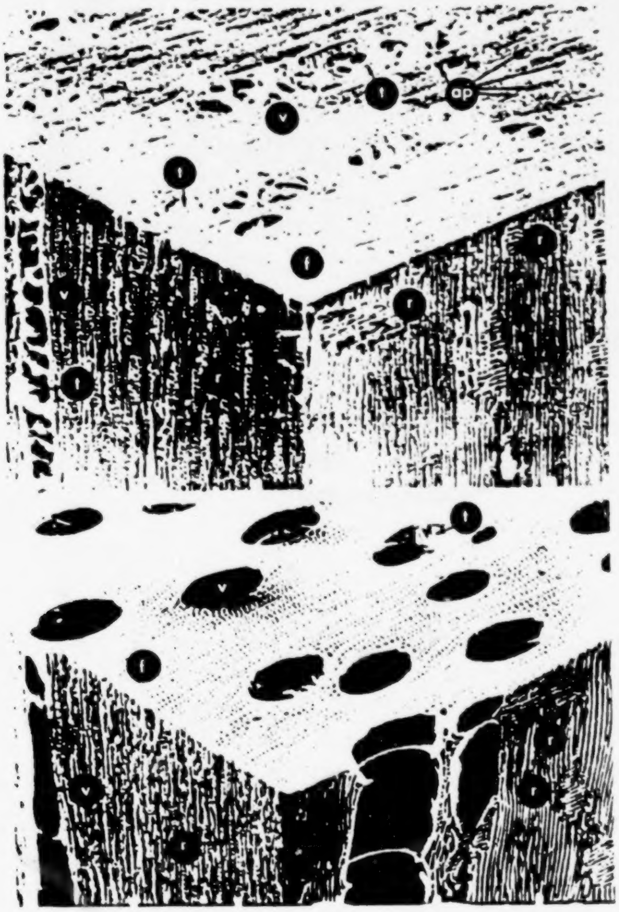

Fig. 7. Scanning electron micrograph of a small cube of the hardwood *Eucalyptus citriodora* (top) and *E. regnans* (bottom) showing rays (r), fibre tracheids (f), vessels (v), tyloses (t), axial parenchyma (ap) (unit distance 300 x 10^{-6} m).

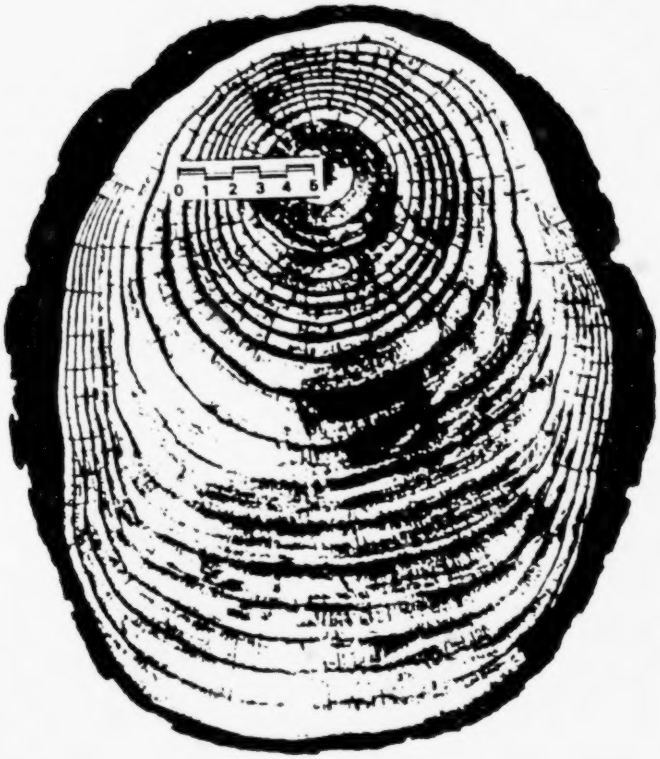

Fig. 8. Cross-section of a log of Pinus radiata taken from a tree that had been blown over after approximately 10 years of normal growth - note the excessive development of compression wood on the lower side (scale in cm).

MECHANICAL PROPERTIES OF WOOD

Leslie D. Armstrong[1/]

The engineer requires an accurate knowledge of the mechanical properties of the large variety of species of wood before he can utilize timber for engineering purposes. He also needs to know the mode of resistance of wood to various types of loading. The wood may be used in the green or air-dry condition, it may be subjected to various types of exposure and it may contain defects such as knots, gum veins, sloping grain, checks, etc., all of which affect the mechanical properties.

An accurate determination of the strength properties of each species of wood can only be made under standard conditions of laboratory testing. The wood must be free of defects, i.e. it must be clear wood, the temperature and moisture content of the wood must be controlled to a selected value and specimens of standard size must be subjected to accepted modes of testing under the various types of loading. The number and type of standard tests carried out differ with various authorities but in Australia it is normal practice to conduct strength tests in static bending, impact, compression parallel and perpendicular to the grain, hardness, shear parallel to the grain, both radial and tangential to the growth rings, cleavage and torsion. The test in torsion is not referred to in any standard. The influence on the elastic properties of wood of such factors as temperature, moisture content, duration of loading, defects, etc. need to be determined separately and allowed for in deriving design stresses based on the mechanical properties of clear wood for each species.

The methods used in Australia for the testing of small clear specimens of timber to determine their strength properties are described in detail by Mack (1979). Methods of sampling and the procedures for the correction of strength properties for moisture content and temperature are also described.

In this paper, the standard tests carried out on clear wood and the typical behaviour occurring in each case will be described. The tests are made at 20°C on green wood cut from the tree and on wood dried to a moisture content of 12 per cent, based on the oven-dry weight, according

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[1/] Until mid-1982 an officer of CSIRO, Division of Building Research, Melbourne, Australia.

to the standard testing procedures of British Standard No. 373-1957, Methods of Testing Small Clear Specimens of Timber, and the ASTM Standard D143-52, 1972, Standard Methods for Testing Small Clear Specimens of Timber. Nominal specific gravity and moisture determinations are made on each specimen. The method used in sampling timber for the evaluation of strength properties is described in Forest Products Technical Note No. 5, 1969.

1. THE STRENGTH PROPERTIES OF WOOD

1.1 Tension

Tensile tests on wood are not included in standard mechanical testing procedures because of the difficulties in obtaining straight-grained, defect-free material and further, because of the difficulties of eliminating the effects on the test results of the end loading attachments. There is a tendency for the wood to crush or shear at the attachments. In practical applications, the full tensile strength of a member is rarely attained because of the lower mechanical properties of the joints or attachments used to connect members.

Straight-grained, defect-free wood has a very high strength in tension parallel to the grain. For example, the average ultimate tensile strength parallel to the grain for dry hoop pine is about 130 MPa and that for dry mountain ash is about 185 MPa. In comparison, the yield stress for mild steel is about 250 MPa.

The tensile strength of wood is very dependent on the angle between the direction of the applied load and the direction of the orientation of the wood fibres, i.e. the direction of the grain of the wood. The tensile strength perpendicular to the grain is about 1/25 of that parallel to the grain for green wood and about 1/45 for seasoned wood. Large reductions in tensile strength occur even with small grain slopes. When knots are present in the wood, the grain slope in the immediate vicinity of a knot is usually steep with respect to the general grain direction and the tensile strength of the material is considerably reduced. The effects of grain angle and knots are taken into account when timber is sorted for structural purposes by the application of grading rules.

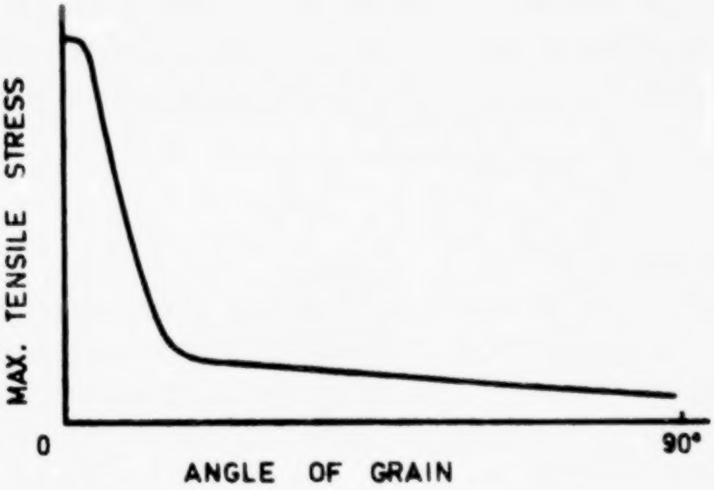

Figure 1. Relationship between maximum tensile stress and angle of grain

The stress-strain curve for wood in tension parallel to the grain is linear almost to the ultimate stress value (90% level) with little plastic deformation.

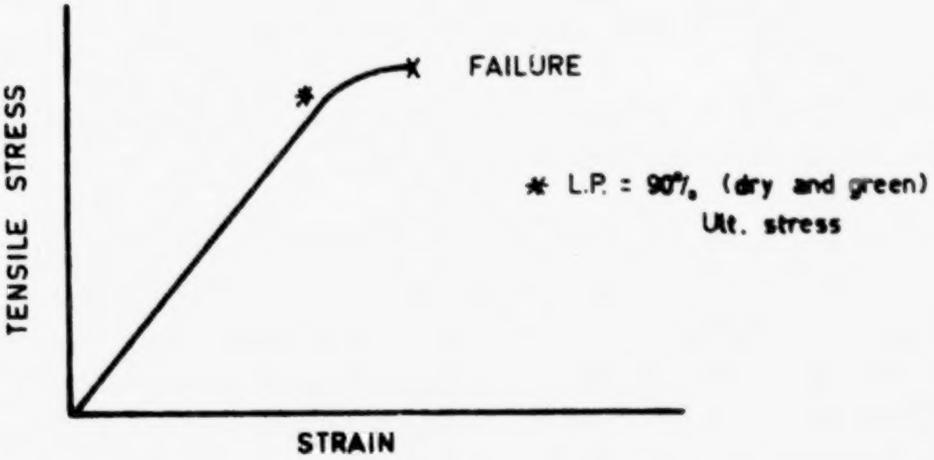

Figure 2. Stress-strain curve for wood in tension parallel to the grain

As the wood does not deform rapidly at high tensile stresses, stress concentrations are not relieved to any appreciable extent; hence, stress concentrations should be avoided. Failure may be splintery in nature in the case of thick-walled fibres failing near the middle lamella or of brittle appearance where thin-walled fibres break across the cells.

1.2 Compression

(a) Parallel to the grain

The standard specimen is 200 mm long by 50 mm square in cross-section. Rate of deformation during test is 0.6 mm/min. Longitudinal deformation is measured by means of a Linear Variable Differential transducer and the load-deformation curve is plotted automatically on a chart recorder. Specimens in the green condition and at 12% moisture content are tested at 20°C. Density and moisture content determinations are made on each specimen.

An alternative specimen sometimes used in compression testing is 60 mm long by 20 mm square tested at a rate of deformation of 0.18 mm/minute.

The maximum crushing strength of wood parallel to the grain is about one-quarter of the ultimate tensile stress. The maximum crushing stress for green Douglas fir (oregon) is about 27 MPa and for seasoned oregon is 51 MPa. The values for mountain ash and grey ironbark, hardwoods, at 12% moisture content are about 63 MPa and 96 MPa respectively.

The moduli of elasticity for wood in compression and tension parallel to the grain are approximately equal in value.

The stress-strain curve for wood in compression is different from that for tension. The curve is linear to a stress level of 65 to 80% of the maximum value in compression in dry and green wood respectively. Following the Limit of Proportionality, the strain increases at an increasing rate with stress, the curve reaches a peak and finally falls as considerable deformation occurs due to the slender wood fibres buckling laterally. The buckling of individual fibres is accompanied by separation in the vicinity of the medullary ray cells which are disposed in a radial direction with respect to the growth rings of the wood. Whereas the longitudinal fibres lend lateral support to each other between medullary rays, the lack of such support in the vicinity of the radial rays permits buckling to occur. The line of failure on the face tangential to the growth rings is along the plane of maximum shear stress which is about 60° to the direction of loading, compared with 45° for isotropic materials. The line of failure on the radial face is at about 90° to the direction of loading and is parallel to the medullary ray cells. A further mode of failure is that of the wedge and split in which two included shear planes form a wedge towards the centre of the width of the specimen.

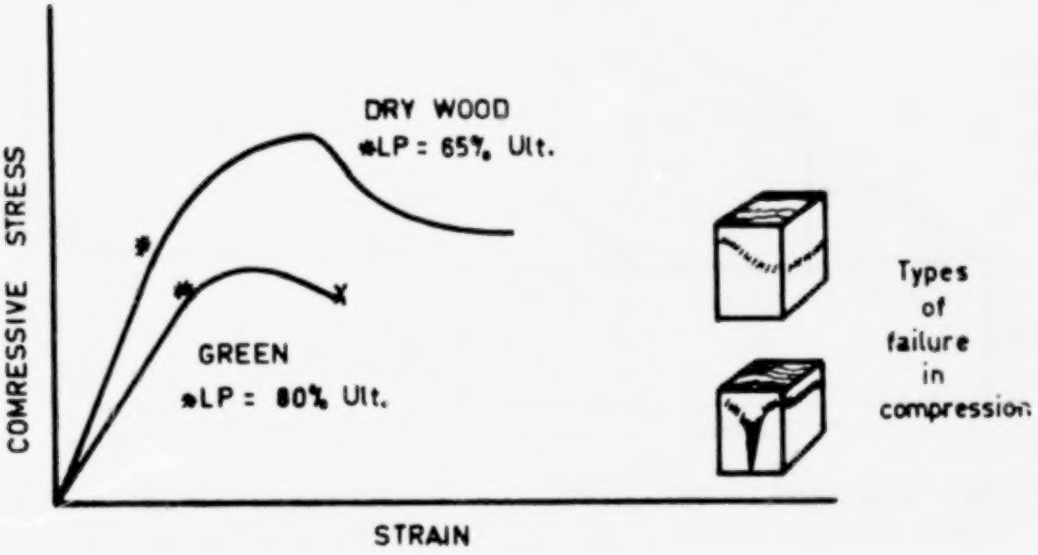

Figure 3. Stress-strain curves for wood in compression parallel to the grain

Quantities measured - maximum crushing stress, stress at limit of proportionality, modulus of elasticity.

(b) Compression perpendicular to the grain

Specimens of two sizes are used in determining the properties of wood in compression perpendicular to the grain. One specimen is 150 mm long and 50 mm square in cross-section (American standard). The specimen is supported on one of the long flat faces and a loading block, 50 mm square, is applied to the opposite face and over the middle third of the length of the specimen. The load is applied to the radial or the tangential face with respect to the growth rings and the specimens are initially machined so that perfect radial or tangential faces exist. The second type of specimen is a cube of 50 mm per side (British standard) tested in a similar manner to the long specimen with the exception that the loading block of 50 mm x 50 mm covers the entire face of the specimen under test. The specimens are deformed at the rate of 0.3 mm/min; corresponding with the American specification, to a total deformation of 2.5 mm. The load required to cause this deformation is accepted as the compressive strength perpendicular to the grain.

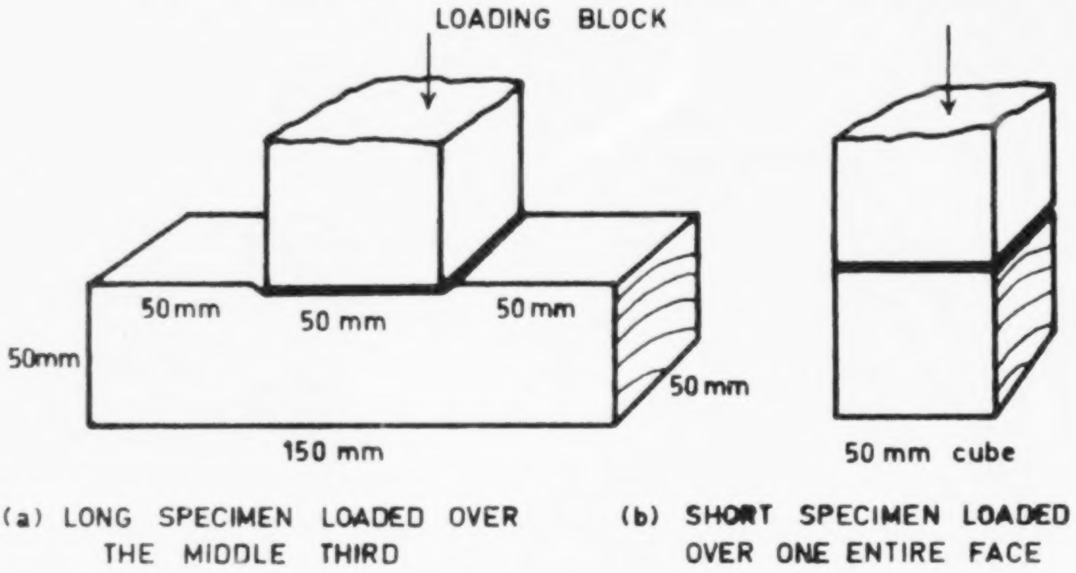
LOADING BLOCK
50mm
50 mm
50 mm
50mm
50 mm
150 mm
50 mm cube
(a) LONG SPECIMEN LOADED OVER THE MIDDLE THIRD
(b) SHORT SPECIMEN LOADED OVER ONE ENTIRE FACE

Figure 4. Compression test perpendicular to the grain

The load-deformation curve for wood in compression perpendicular to the grain is initially linear. Beyond the limit of proportionality, the deformation continues to increase for little change in load. The hollow fibres squash flat and the wood densifies until the thickness of the wood is reduced to about one third of the original value. Following this state, the load increases sharply with further compressionn of the densified material.

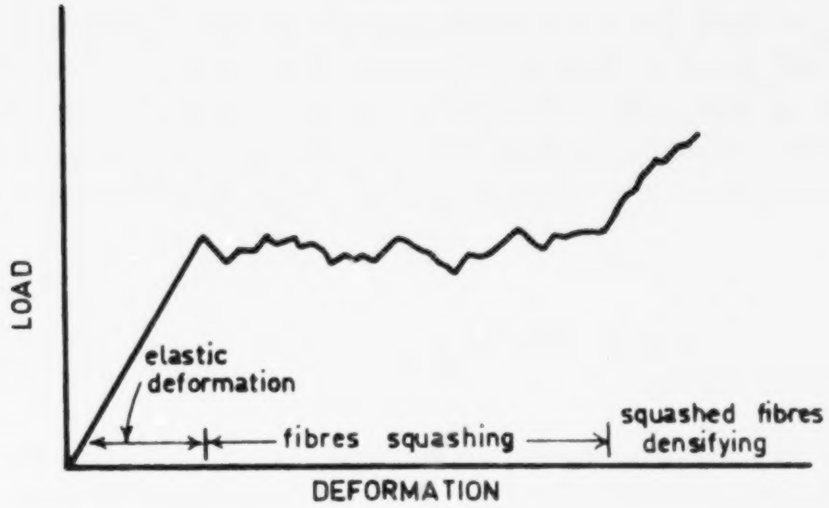

Figure 5. Load-deformation curve for wood in compression perpendicular to the grain

With the specimen loaded over only a portion of its area, the resistance to the load is proportional to the loaded area and the loaded perimeter. The material on each side of the loaded area lends support in opposing expansion of the loaded area in the direction at right angles to the direction of loading and, in addition, support is provided to the loaded fibres in the direction of loading. Experiments have shown that where the loaded edges are sufficiently remote from the edges of the piece of timber, such as the case of loading a specimen over the middle third of the length, the bearing stress, determined from a 50 mm cube loaded over one face, could be increased by a factor f, where

$$f = 1 + P/A \quad \text{(in. units)}$$

where p is the loaded perimeter and A is the loaded area.

In the specimen loaded over the total bearing area, no perimeter effects exist.

For timber loaded in compression at an angle between 0^o and 90^o to the grain, the compressive strength may be estimated from Hankinson's formula which is given in the SAA Timber Engineering Code.

1.3 Bending

Because of the disparity in the compressive and tensile strengths parallel to the grain, neither provides a suitable basis for the design of beams. It is more convenient to determine the bending strength by test and to derive design stresses from the test results. An approximate value of the extreme fibre stress at failure, the modulus of rupture, is calculated as

$$\text{MOR} = \frac{\text{Maximum bending moment}}{\text{Section modulus}}$$

Specimens of two sizes may be used in standard testing in centre-point bending. The dimensions are 750 mm in length x 50 mm square in cross-section tested over a span of 700 mm and 300 mm x 20 mm square, span 280 mm. The beams are freely supported and loaded in bending in the radial direction at the centre of the span. The rate of deformation is 2.5 mm/min for the larger specimen and 1 mm/min for the smaller specimen. Load-deflection curves are recorded on charts using L.V.D.T.*/ devices to measure deflection. Modulus of rupture, stress at limit of proportionality and modulus of elasticity are determined. The modulus of elasticity calculated from the data in this test may be up to 16% lower than the true modulus because of the inclusion of deflection due to shear.

The load-deflection curve is linear in the early stage and following the limit of proportionality, the deflection increases appreciably with a relatively small increase in load. After a maximum load value is reached the load values decrease with increasing deflection until failure results.

The mode of failure and stress distribution in a beam are largely determined by stress-strain relations for compression and tension parallel to the grain. As the load on a beam increases, the stresses increase linearly until the limit of proportionality in compression is exceeded at the extreme fibre on the compression side of the beam. The extreme fibres begin to buckle, but initially the deformation is small and their load-carrying capacity probably remains fairly constant. Fibres below the extreme fibre buckle in turn to produce a macroscopic wrinkle at one or more sections in the compression zone of the beam. As this load sharing process continues across the depth of the compression zone, the compression wrinkle progresses towards mid-height of the beam and the stress over much of the compression zone is approximately constant and equal to the maximum crushing stress. The extreme fibre stress in tension steadily increases until the maximum tensile stress is reached at the extreme fibres and failure results. Just prior to failure, the stress distribution on the compression side of the beam is approximately rectangular over most of the section and equal to the maximum crushing stress, decreasing rapidly to zero value at the neutral plane, whereas on the tension side of the beam the stress distribution is approximately linear, varying from zero at the neutral plane to the value of the maximum tensile stress at the extreme tensile fibres. The neutral plane moves from the initial position at mid-height of the beam towards the tension face. The stress distribution assumed for calculating the modulus of rupture varies linearly from equal maxima values at the extreme fibres in compression and tension to zero at the neutral plane which is assumed to be at mid-height of the beam. The calculated value of the modulus of rupture in compression is about twice the actual maximum compressive stress and in tension, the value is about half the actual maximum tensile stress.

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*/ Linear Variable Differential Transducer

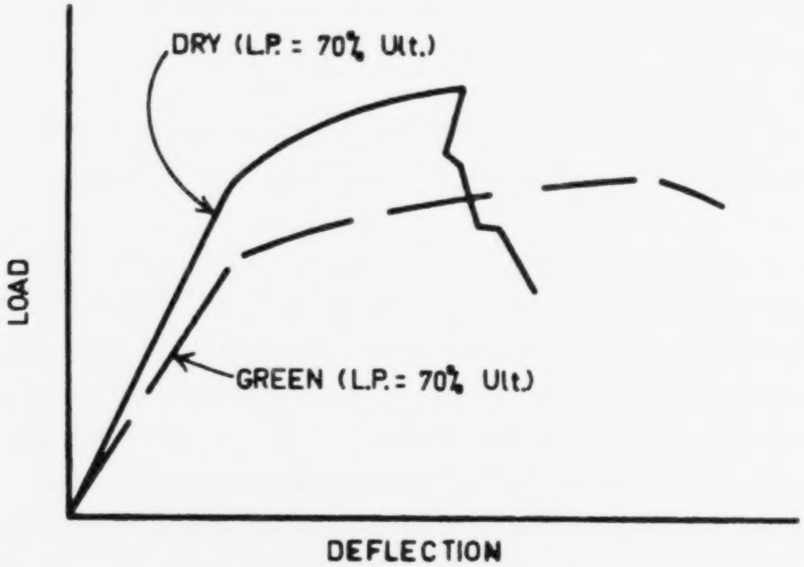

Figure 6. Load-deflection curves for wood in bending parallel to the grain

The nature of the failure on the tension side of the beam varies with species and may be splintery or brittle in appearance. If loading is stopped just prior to failure on the tension side of the beam, even though compression wrinkles are present, and the beam is turned upside down and reloaded, the maximum load required to break the beam is nearly as high as that which would have been needed to break the beam in the first case. The buckled fibres in the previous compression zone are pulled straight in their new role in the tension zone, while compression wrinkles now occur in the new compression zone. The resultant fracture on the tension side of the beam is brittle in nature.

Modulus of rupture is dependent on the type of loading on the beam. It is lower for a beam subjected to loading at the quarter points ('four-point' loading) than for a beam loaded at mid-span ('centre-point' loading). The difference varies with species but is about 10% on the average. In four-point bending, the maximum load depends on the weakest section between the load points where all sections are subjected to the maximum bending moment, whereas in centre-point bending the maximum load depends on the strength of the material at sections close to the centre of the span where the bending moment is at a maximum value. The chance of the weakest section of the beam being at midspan is relatively small so the modulus of rupture of a beam in centre-point bending tends to be higher than that in four-point bending.

The centre-point values are taken as the basis for design stresses, appropriate consideration being given to other types of loading.

The modulus of elasticity in centre-point bending is calculated from the load-deflection curve for the full span and is up to 16% lower than that calculated from the deflection in four-point bending, which is measured between the load points. This is because in centre-point bending the deflection over the full span is due to the effects of bending moment and shearing force, whereas the deflection between the load points in four-point bending is due to bending moment only, as the shearing force is zero in this region. The modulus of elasticity of wood parallel to the grain has the same value whether determined by tension, compression or pure bending.

Because beams in practice are generally subject to shearing force, the modulus of elasticity quoted for design purposes is that obtained from tests in centre-point bending, and thus no extra allowance for shear deflection need be made for solid beams. When shear deflection needs to be considered as, for example, in the design of I-beams, an appropriate increase in modulus of elasticity is made to bring it close to the value for pure bending.

1.4 Shear

A block shear test is made on cubic specimens of 50 mm or 20 mm dimension in accordance with the British standard. The specimen is attached firmly in a steel loading block and tested in single shear in the direction of the fibres and over sections radial and tangential to the growth rings. The distance between the sheared edges is 3.2 mm in the 50 mm specimen and 1.6 mm in the 20 mm specimen. The specimen is deformed at the rate of 0.6 mm/min. for both sizes. A torsion test is also made at CSIRO on a cylindrical section of solid wood of 38 mm diameter.

The shear strengths from block shear and torsion tests are closely correlated but the value from the torsion test is somewhat higher probably because the torsion test is freer from stress concentrations and tensile stresses perpendicular to the grain inevitably induced in the block shear test.

Wood is much weaker in shear parallel to the fibres than perpendicular to the fibres. Hence, in beams subject to excessive shearing force, failure is by longitudinal shear and not by transverse fracture.

1.5 Impact

The impact tests for wood tested in Australia are not included in the British or American standards. A toughness impact test, described in Technical Bulletin 479, US Department of Agriculture, is made on a specimen 250 mm long and 16 mm square in cross-section. The specimen with the fibres parallel to the length is freely supported at each end and loaded at the centre in the radial or tangential direction by means of a high speed pendulum. The work done in breaking the specimen is measured.

A further type of impact test, the Izod test, specified in British standards such as DTD-36B, 1939, is performed on a cantilever specimen of 22 mm square cross-section, notched as in the Charpy impact test for metals. Load is applied to the end of the cantilever by means of a high speed pendulum. The fibres are parallel to the length of the specimen and the load is applied in the radial or tangential direction with respect to the growth rings.

Impact testing is useful as a means of estimating the ability of wood to absorb shock loads and further as a means of detecting the presence of certain defects in wood not obvious to visual inspection but which should be eliminated in certain uses of wood. The impact strength of wood is sensitive, for example, to the presence of brittle heart and incipient decay.

1.6 Cleavage

The cleavage specimen is 45 mm long and 20 mm square in cross-section or 95 x 50 x 50 mm with the fibres parallel to the length. A deep groove of special shape is machined across one end face of the specimen to permit loading perpendicular to the grain and in the radial or tangential directions. The remaining area, subjected to cleavage, is approximately 20 mm square in the small specimen and 76.2 x 50 mm in the larger specimen. The cleavage test is a combination of tension perpendicular to the grain and splitting. The rate of lateral deformation is 2.5 mm/min. The load necessary to split the specimen per unit width is referred to as the cleavage strength and is indicative of the splitting tendency of wood. The result is of value, for example, in assessing nail and screw holding properties. Such factors as orientation of growth rings, irregularities of grain, dimensions of medullary rays, presence of resin canals and arrangements of the different tissues, affect the resistance to splitting.

1.7 Hardness (Janka)

The force required to indent in a piece of wood a ball of 11.28 mm diameter to a depth of 5.64 mm at a rate of 6.5 mm/min. is known as the Janka hardness value. Hardness is determined for the radial, tangential and end surfaces. The specimen size is 150 x 50 x 50 mm.

The hardness value correlates closely with the density of the wood.

2. FACTORS AFFECTING THE MECHANICAL PROPERTIES OF CLEAR WOOD

2.1 Species

The mechanical properties of different species of wood vary considerably, some species being many times stronger than others.

Within any one species there is a wide variation in the properties of wood. In species of low strength some pieces of wood may be three or four times as strong as other pieces of the same species. In eucalypts, however, the ratio between the strongest and weakest pieces is about two. The variation in strength within a species is such that great importance should not be attached to small differences, say less than about 10%, in the average properties of different species.

The variation in strength properties within a species is due to such factors as density, rate of growth, percentage late wood and the conditions of tree growth. Environmental factors affecting tree growth, such as height above sea-level, geographical location, climate, soil conditions, aspect and spacing between trees, all have an effect on density. Because of the great number of factors involved and their interactions, little clear evidence is available on their separate influences.

2.2 Age

The age of the tree, at least in the early years of its life, has an effect on the strength of the wood. Strength increases fairly rapidly with age and after about 30 years full strength is achieved, although it will vary from year to year with seasonal conditions.

The rate of growth, that is the number of rings per inch, has been taken as an indicator of strength. Specifications often impose limits for rate of growth because very fast-grown and very slowly-grown wood is often weaker than that of more moderate rate of grwoth. During the early years of the life of the tree, growth is rapid and the wood is of low strength compared with that laid down during mature years. In the years following maturity, the rate of growth is very slow and the wood is of low strength. It has been shown that the apparent high correlation between rate of growth and strength does not exist but age rather than rate of growth appears to be the factor controlling the strength of the wood.

2.3 Position in Tree

The way in which the strength properties vary with height of the tree depends on the species. In softwoods, the wood from near the butt of the tree is usually denser, stronger and harder than that from near the top, but in some of the eucalypts the reverse holds true. The effect of height in tree, however, is usually variable and only rarely of practical significance.

The variation in strength of wood in the radial direction with distance from the pith is of importance, material from near the pith tending to be weaker in some species. Away from the vicinity of the pith, strength properties tend to vary erratically, presumably with seasonal growing conditions. In plantation-grown species, the variation of strength properties with distance from pith can be very large. As an example, in 40 year old trees of radiata pine, a twofold increase in density and a fourfold increase in bending strength have been observed in samples taken from pith to bark. A rise of 50% in density and 100% in bending strength is not unusual in 30 to 40 year old trees of this species.

The zone of wood called 'brittle heart' which surrounds the pith in many hardwoods contains wood fibres having compression failures in the walls. Such failure are believed to occur from excessive compressive stresses arising at the centre of the tree during growth. The extent of this zone varies with species and with the diameter of the tree, but in general, it represents only a small proportion of the volume of the tree. The static strength properties of brittle heart are similar to those of normal wood provided no decay is present but the impact strength is very low; hence it is usually not used for structural purposes.

2.4 Percentage Late Wood

Percentage late wood is the proportion of dense wood laid down towards the close of each growing season to the total wood laid down for the year. It is closely correlated with density so a high percentage of late wood is generally a good indication of high strength. This fact can be used to advantage in the selection of wood with prominent bands of late wood. In the USA, higher working stresses are permitted for Douglas fir in which the late wood exceeds 35% of the total wood.

2.5 Density

Density is highly correlated with strength. The specific gravity of wood substance is 1.5 regardless of species, but the arrangement of the substance in the cells and in the total structure reduces the density to a much lower value. Strength depends very much on the relation between the cell wall thickness and the width of the cell lumen. This relation varies with the growth conditions and the age of the tree. The following approximate relationships between strength and density of both green and air-dry material have been found for variability within a species:

$$\text{Strength} = K.\text{density}^{n}$$

where n = 1.25 for modulus of rupture and maximum compression strength parallel to grain
= 2 to 2.25 for impact strength
= 2.5 for compression perpendicular to the grain and hardness
K varies with the property and the moisture content of the wood
Density is calculated on the weight of oven-dry wood and the volume at the particular moisture content.

The relations indicate that the major strength properties (modulus of rupture, compressive strength parallel to grain) increase approximately in proportion to density. Compression perpendicular to grain, hardness and impact, increase at a much more rapid rate.

Despite the high correlation, only about 80% of the variation in strength is due to variation in density. Part of the discrepancy is due to extractives and deposits which add to density but not to strength. Consequently even density is unable to predict the strength of a piece of wood with high precision. Nevertheless, density can be useful in reducing the chances of obtaining pieces of timber with strengths lower than particular values. Certain specifications, particularly for timber for aircraft use, set minimum densities for each piece in an endeavour to ensure that the required minimum strength is attained.

2.6 Reaction Wood

Compression wood, formed in bent or leaning trees of softwood species, has abnormally high shrinkage, is denser and somewhat stronger than normal wood but is very brittle. In a severe form it is noticeable as dark-coloured bands but in a mild form it is not readily detected by visual examination.

Tension wood, formed in bent or leaning trees of hardwood species, has a high shrinkage but has little effect on strength properties. It is detectable in sawn wood by the stringy appearance of the surface.

2.7 Variability of Clear Timber Within a Species

The variability in the mechanical properties of wood within a species makes it a time-consuming task to determine those properties. A sufficient number of specimens per tree and a sufficient number of trees must be tested to determine the species mean with adequate precision. To estimate the species mean to within ±5%, at least 5 to 20 trees are sampled.

The results of such tests show that, in each case, a large number of values for each property are distributed close to the mean value with a small number distributed well above and below the mean value. The amount of the variability is defined from the mean value ($\bar{x}$) and the standard deviation (σ). The greater the value of σ, the greater the dispersion of the individual values of a property about the mean value and the greater the probability of obtaining material exhibiting very high or, more importantly, very low properties. Approximately 95% of the material has strength values lying within the range of $\pm 2\sigma$, so that the value $\bar{x} - 2\sigma$ will be exceeded by all but 2.5% of the material of the species. An estimate of the variability from the mean is essential for deriving design stresses.

The value $\sigma/\bar{x}$ expressed as a percentage is called the coefficient of variation and is often used as a measure of variability. Its disadvantage is that it is dependent upon the mean, so for two species with the same standard deviation, the weaker will have the larger coefficient of variation.

Coefficient of variation values for the strength properties of green wood of 50 species tested in the USA are as follows:

Property	COV (%)
Static bending	
Modulus of rupture	16
Modulus of elasticity	22
Compression parallel to grain	
Maximum crushing stress	18
Modulus of elasticity	29
Shear parallel to grain	
Maximum shear stress	14
Compression perpendicular to grain	
Stress at L.P.	28
Tension perpendicular to grain	
Maximum tensile stress	25
Hardness	
End	17
Side	20
Toughness	34

(Values for air-dry wood may be assumed to be similar to above)

Similar values to those given in the table have been determined in tests on Australian hardwoods.

2.8 Moisture Content

Water is contained in the wood cell as free water in the lumen and as combined water in the wood tissue. The total weight of water in wood may exceed the weight of dry wood tissue. Removal of the free water during seasoning of wood does not affect the strength properties of the material. The moisture content of the wood, expressed as a percentage of the oven-dry weight of the wood substance, is approximately 30% after the free water is evaporated but while the cell wall is still saturated. This level is referred to as the fibre saturation point. As drying continues below fibre saturation with removal of the combined water, the strength properties increase by between 1.5 and 5% for each 1% reduction in moisture content (Wilson 1932). With uptake of water in dry wood similar reductions in strength occur.

The average percentage changes in various properties per 1% change in moisture content are as follows:

Property	% change per % change in m.c.
Modulus of rupture	4
Modulus of elasticity	1.5
Maximum crushing strength	5
Maximum shearing strength	3
Compression perpendicular to grain	5
Tension perpendicular to grain	2
Hardness	
End	4
Side	3
Torsion	
Maximum shear stress	3
Modulus of rigidity	2

In the case of impact strength, some species show an increase in this property with drying, some a reduction at first followed by an increase as the moisture content is reduced below 12% and other species showing a continuing reduction.

The following diagram represents the change in some properties with change in moisture content.

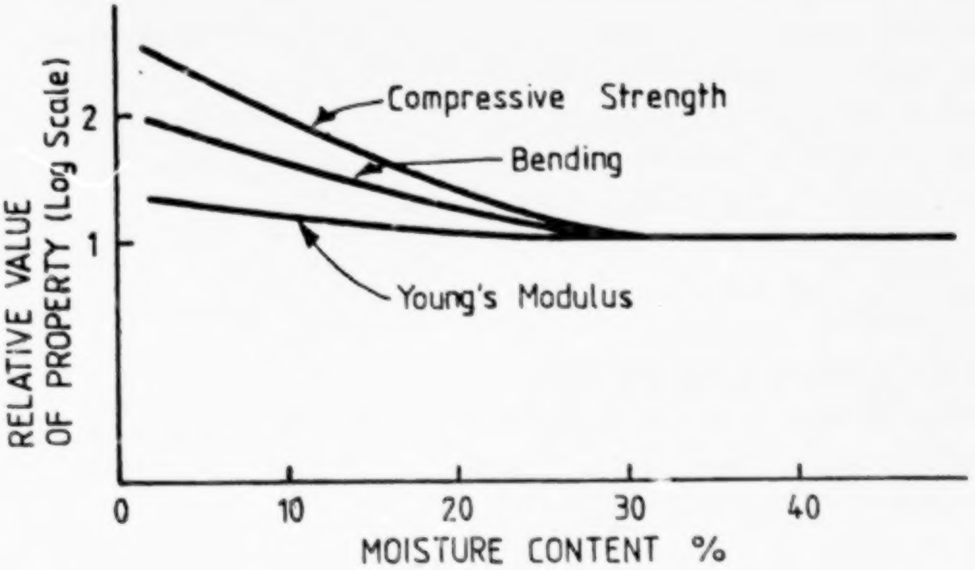

Figure 7. Variation of mechanical properties of wood with moisture content

The following approximate relationships have been taken from the previous diagram:

(a) $\frac{\text{Maximum crushing strength at 12\% m.c.}}{\text{Maximum crushing strength at 30\% m.c.}} = 1.9$

(b) $\frac{\text{Modulus of rupture at 12\% m.c.}}{\text{Modulus of rupture at 30\% m.c.}} = 1.6$

(c) $\frac{\text{Modulus of elasticity at 12\% m.c.}}{\text{Modulus of elasticity at 30\% m.c.}} = 1.2$

When comparing the properties of different species, or of individual pieces of wood, the values should be those appropriate to the same moisture content.

Drying is a slow process for hardwoods and for larger sizes of softwoods and hence, in some cases, structural timber may be green or only partly dried, when used. This applies also for imported timbers such as Douglas fir (oregon) because it is imported in large flitches, which do not dry appreciably in transit or storage, and which are resawn to smaller sizes on order. Under the unrestricted drying which usually occurs in structures, checks and other defects may develop in timber members which can offset the increase in strength due to drying. Consequently, working stresses are based on the strength of green timber.

2.9 Temperature and Strength

(a) Immediate effect of temperature

Generally, with other conditions remaining the same, when the temperature of wood is raised above normal, it tends to become weaker in most strength properties, and when the temperature is lowered, it becomes stronger.

Temperature may also affect strength by altering the relative humidity of the atmosphere and hence the moisture content of the timber. Often an increase in temperature is accompanied by a reduction in moisture content and so the weakening due to temperature alone may be offset by the increase in strength which accompanies drying. On the other hand, high humidity may accompany high temperatures and the weakening effects of higher moisture content and temperature will be additive. The following discussion will be limited to timber at constant moisture content.

The effect of temperature alone on strength is immediate, and its magnitude depends upon the moisture content of the wood and, when the temperature is elevated, upon the time of exposure. For most structural uses under ordinary atmospheric conditions, wood exposed to temperatures above normal, if the exposure is for a limited period and the temperature is not excessive, can be expected to recover essentially all its original strength when the temperature is reduced to normal. Experiments indicate that air dry wood can probably be exposed to temperatures up to about 65°C for a year or more without an important permanent loss in most strength properties, but its strength while heated will be temporarily reduced as compared to the strength at normal temperature.

The approximate immediate effect of temperature on most static strength properties of dry wood (12% moisture content) within the range of -15^{o} to 65^{o}C can be estimated as an increase or a decrease in the strength at 20^{o}C of 1% per degree Celsius decrease or increase in temperature (Sulzberger 1943). The change in properties will be greater if the moisture content is high and less if the moisture content is low. In some geographical locations fairly high temperatures are commonly experienced, but the accompanying relative humidity is ordinarily quite low. Wood exposed to such conditions will generally have a low moisture content, and the immediate effect of the high temperature is not so pronounced as in locations where wood has a higher moisture content.

Figure 8a shows the approximate temperature and moisture content relations that apply for modulus of rupture in bending.

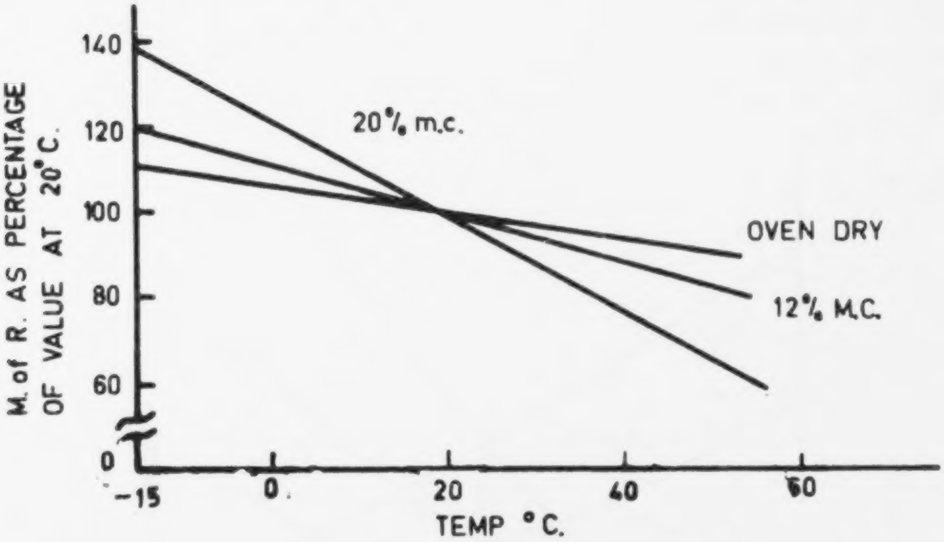

Figure 8a. Relationship between modulus of rupture and temperature for wood at various moisture contents

Tests conducted on wood at about -100^{o}C show that the important strength properties of dry wood in bending and in compression, including stiffness and shock resistance, are much higher at that extremely low temperature than at normal temperature.

The compressibility of wood greatly increases when heated providing the moisture content is not too low. The strain in partly seasoned wood subjected to steaming and loaded parallel to the grain is increased greatly at maximum load compared with strain under normal conditions.

Steaming has much less effect upon the tensile properties and the strain at maximum stress is not greatly increased.

As shown in Figure 8b, toughness shows a general trend from a decrease in toughness with rising temperature at low moisture contents to an increase in toughness with temperature at high moisture content. This is possibly because toughness is a function of strength and deflection. Below 12% moisture content, the deflection of a beam does not increase much with rise in temperature so there is little or no increase in its ability to absorb impact loads. Above about 12% moisture content, the deflection of a beam increases with rise in temperature and so toughness tends to increase too.

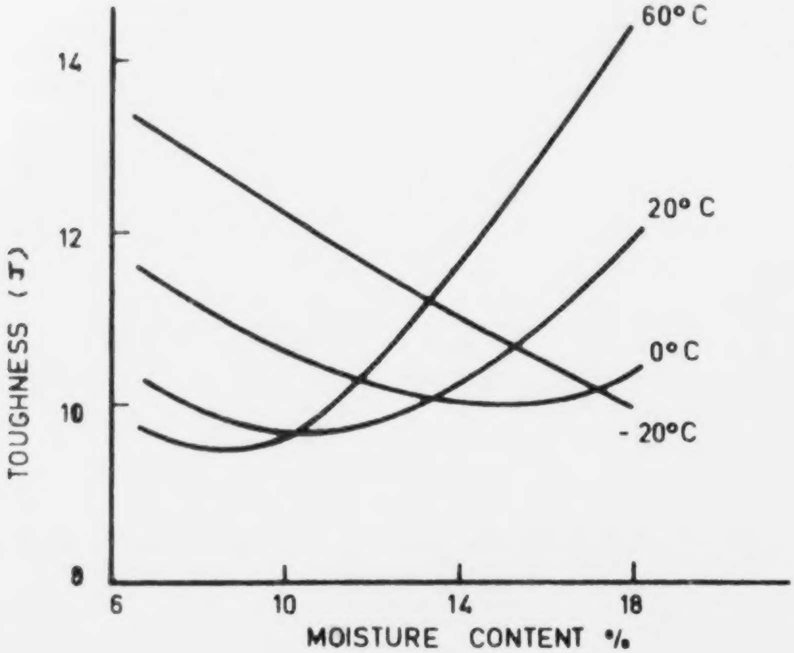

Figure 8b. Variation of toughness of wood (impact resistance) with moisture content at various temperatures

(b) Permanent effect of exposure to high temperatures

When dry wood is exposed to temperatures above 65°C for extended periods of time, it will be permanently weakened, even though the temperature is subsequently reduced and the wood is used at normal temperatures. The permanent or non-recoverable strength loss will depend upon a number of factors including the moisture content and temperature of the wood, the heating medium and time of exposure, and to some extent upon the species and the size of the piece. In the following discussion it should be understood that losses in strength are permanent losses, measured at normal temperature, after exposure to high-temperature conditions for various periods. Reductions in strength would be substantially higher if measured at the elevated temperature.

Broadly, the available data indicate that wet wood will suffer permanent loss in strength if heated above about 45°C. Exposure to higher temperatures will result in increasingly greater strength losses in shorter periods of time as the temperature is increased. Strength properties are affected differently by exposure to high temperatures. The shock resistance of wood as measured by the area under the load-deflection curve (work to maximum load) is the first bending strength property affected to a measurable degree regardless of the species, temperature, or heating medium. Modulus of elasticity, a measure of stiffness, is least affected. The effects of heating on the bending properties of wood exposed to water at 85°C for various periods are shown in Figure 9.

The effect of high temperatures on various species is different but, in general, hardwoods are affected to a considerably greater extent than softwoods.

The heating medium used has a considerable bearing on the amount of reduction of strength that results from exposure of wood at a particular temperature for various periods of time. At all temperatures, exposure to hot water causes somewhat less strength loss in a given period of time than steam; the effect of exposure to a hot press is considerably less than it is for hot water, and the least effect results from exposure to hot, dry air.

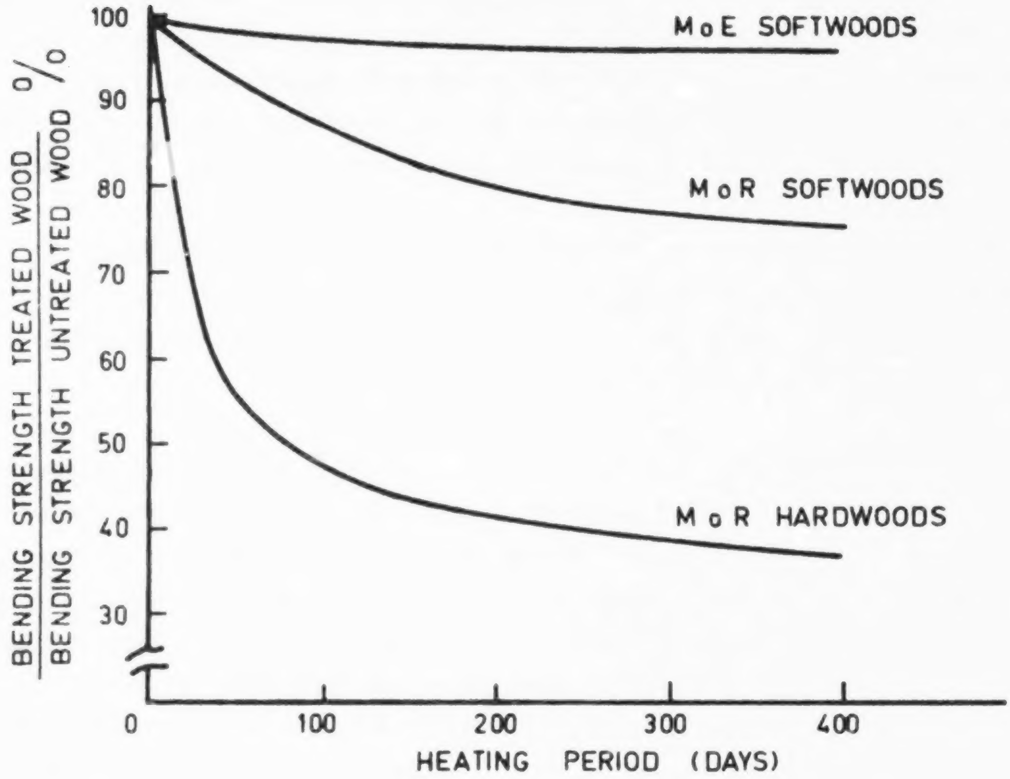

Figure 9. Effect of heating on the bending properties of wood exposed to water at 85°C for various periods then tested at 20°C and 12% moisture content

The effect of exposure to high temperatures on the strength of wood is cumulative. For example, if wood at a particular moisture content is exposed 6 different times to a temperature of say 65°C for 1 month each, the overall effect would be approximately the same as for a single exposure of 6 months.

The shape and size of wood pieces can be expected to influence the overall temperature effect in relation to the heating medium, exposure time, moisture content, and the strength properties considered. If the exposure is for only a short time, so that the inner parts of a large piece do not reach the temperature of the surrounding medium, the immediate effect on the strength properties of the inner parts will be less than for the outer parts. On the other hand, the outer fibres of a piece stressed in bending are subjected to the greatest load and will ordinarily govern the ultimate strength of the piece; hence, the fact that the inner part is at a lower temperature may be of little advantage.

For long-extended exposures, it can be assumed that the entire piece reaches the temperature of the heating medium and will, therefore, be subject to permanent, non-recoverable strength losses through the volume of the piece, regardless of size. It should be recognized, however, that in ordinary construction service, such as in buildings, the temperature of the air surrounding the wood varies considerably during the day and the seasons of the year and that the wood itself, or at least any substantial part of a member, is not likely to reach the maximum temperature of the surrounding air. This is true particularly of the larger or structural members.

In designing a timber structure for exposure in the tropics, the engineer must make allowance for the combined effect of high temperature and high moisture content and the SAA Timber Engineering Code provides for this.

Industrial buildings, in which normal operations lead to the generation of high temperatures and high humidities that may affect the structure, must be designed for the effects of these factors on the strength of wood.

2.10 Duration of Loading

The permissible stresses and moduli of elasticity for structural timbers are derived from the results of standard mechanical tests on the various species, appropriate allowance being made for factors such as material variability, defects, type of engineering structure, service conditions and a factor of safety. Included in the service conditions are the effects of duration of loading on the strength and stiffness of wood.

Most materials exhibit time-dependent behaviour when subjected to sustained loading, i.e. dead load, or continued restraint. Such rheological phenomena are important in the usage of the materials, particularly in engineering application. The rheological behaviour of a material is influenced by its physical and chemical structure, previous history, type and magnitude of loading and the environment in which it is contained. For hygroscopic materials such as wood, the moisture content and fluctations in moisture content, due to the environment, may have a pronounced effect on rheological properties.

(a) Creep in wood and wood products

When a wooden member is subjected to any type of sustained load, it undergoes an immediate deformation which may consist of recoverable and irrecoverable components, dependent upon the magnitude of the stress and the time taken to apply the load. For low stresses, i.e. stresses below about two to three times the permissible stresses used in engineering design, and very short times of loading, i.e. times similar to those occupied in performing standard mechanical tests in a laboratory, the deformation resulting on application of the load may be considered to be elastic in nature. As the time under load is increased, the deformation continues to increase, but at a gradually diminishing rate and consists of a delayed elastic component, which is recoverable when the load is removed, and an irrecoverable component. This time-dependent behaviour is referred to as creep. At low stresses, the creep rate may gradually approach zero.

Factors such as temperature and moisture content affect the amount and the rate of creep, higher values of deformation arising with increases in these factors.

After removal of the applied load, an immediate elastic recovery occurs and it is similar in magnitude to the immediate deformation that occurs when the loads are applied. A further gradual reduction in deformation occurs with time and continues for a considerable period, the rate of recovery gradually approaching zero, with an irrecoverable component, i.e. a flow component, remaining in the wooden member.

Typical creep behaviour in wood is illustrated in Figures 10 and 11.

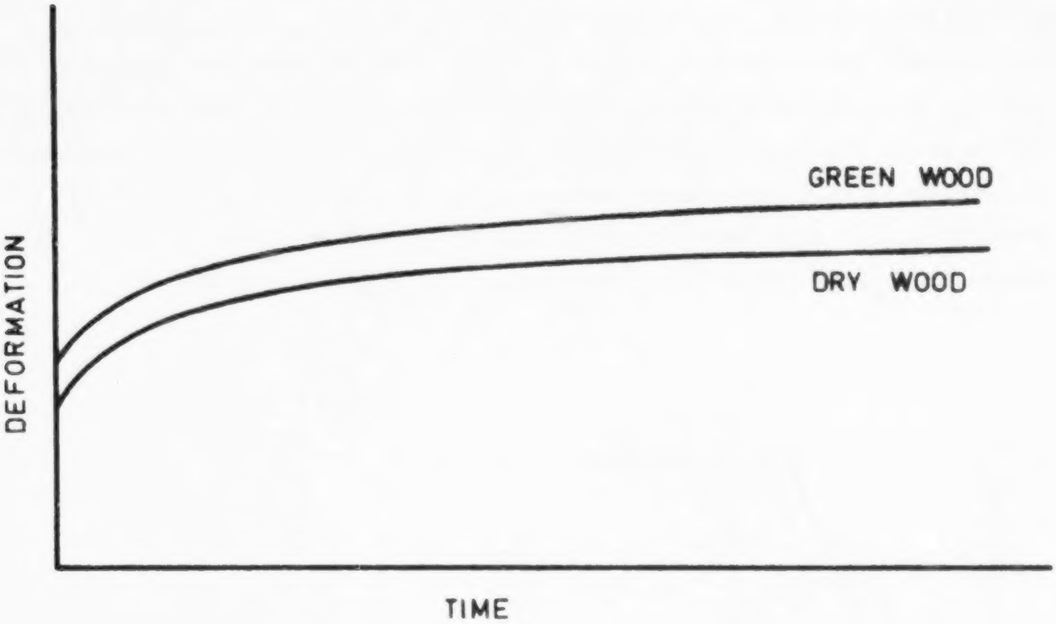

Figure 10. Creep v. time curves for wood at constant conditions of temperature and moisture content

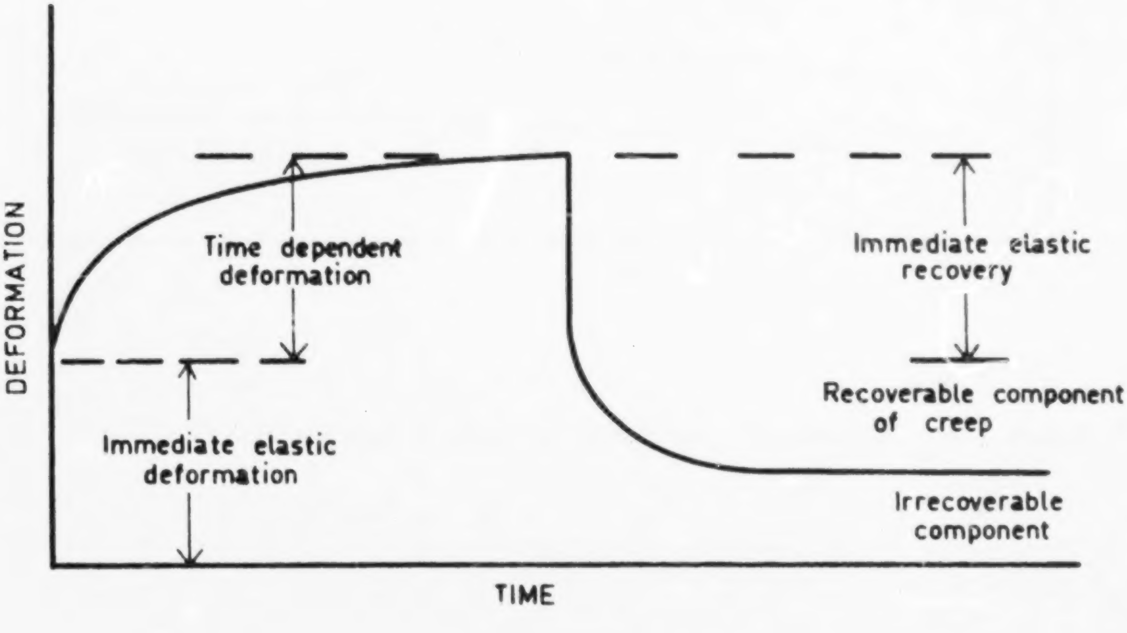
DEFORMATION
Time dependent deformation
Immediate elastic deformation
Immediate elastic recovery
Recoverable component of creep
Irrecoverable component
TIME

Figure 11. Components of creep

At high stress levels, i.e. at stresses above about 55% of the short-term ultimate stress, the initial pattern of behaviour is similar to that already described but, after a period, the deformation increases again at an increasing rate until failure occurs. It is possible that for very low stresses, deformations may vary in this way if the duration of loading is very extensive, however, the periods involved would greatly exceed the economic life of wooden structures. The influence of stress on creep in wood is illustrated in Figures 12a and 12b.

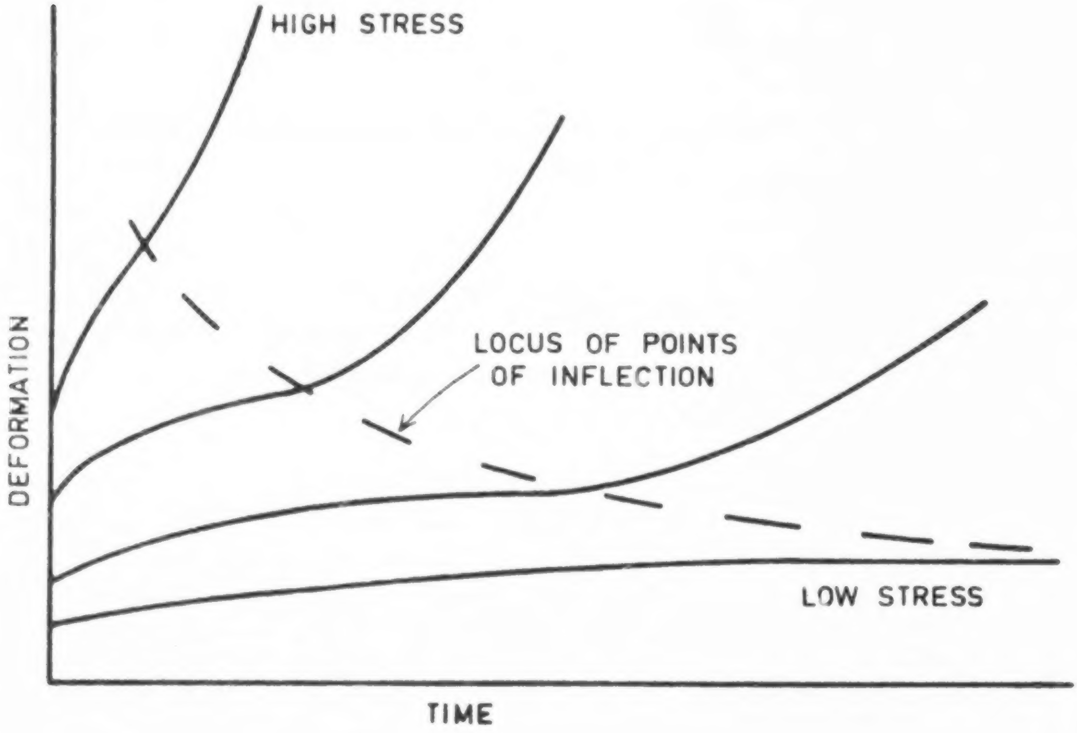

Figure 12a. Deformation-time curve for wood at various stress levels

creep rate becomes very low after that time. In tests on five hardwood species and five softwood species, no marked differences in creep behaviour were evident.

Relative creep increases markedly with increasing temperature, e.g. relative creep at 40°C is about double that at 20°C.

Relative creep is unaffected by the moisture content level of the wood, provided the moisture content does not vary during the period that the wood is under load. Relative creep in green or dry wood in a constant environment is illustrated in Figure 13.

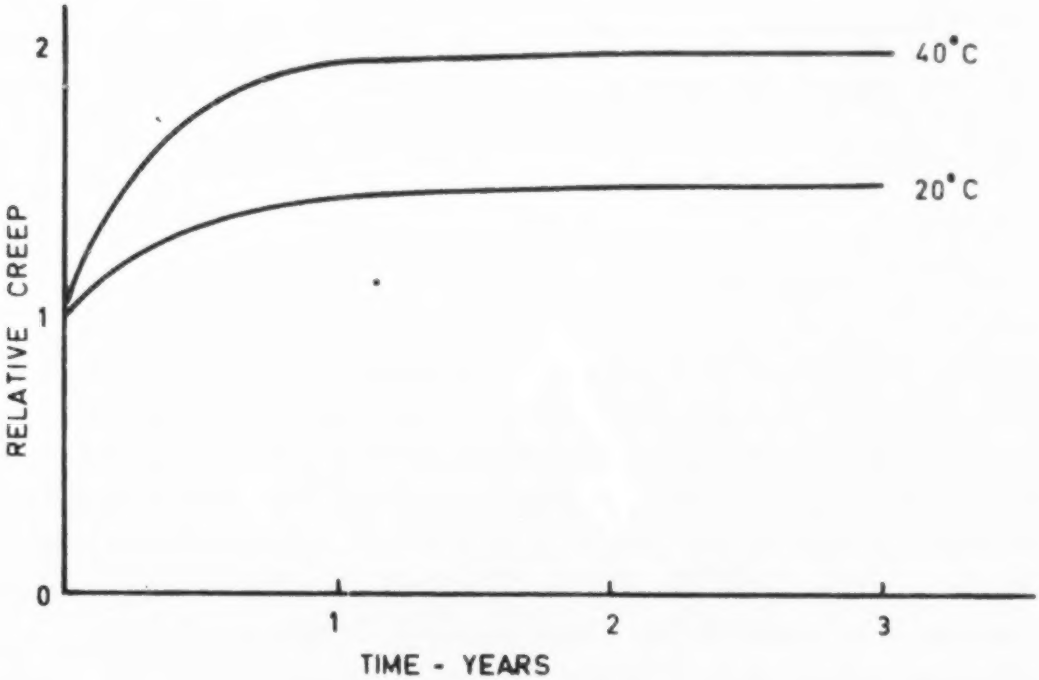

Figure 13. Relative creep in green or dry wood in a constant environment

Some work has been done on creep in wood in compression and tension perpendicular to the grain of the wood, and the amount of creep appears to be slightly greater than that in wood stressed parallel to the grain. After the sustained loads are removed from a wooden member that has been creep rate becomes very low after that time. In tests on five hardwood species and five softwood species, no marked differences in creep behaviour were evident.

Relative creep increases markedly with increasing temperature, e.g. relative creep at 40°C is about double that at 20°C.

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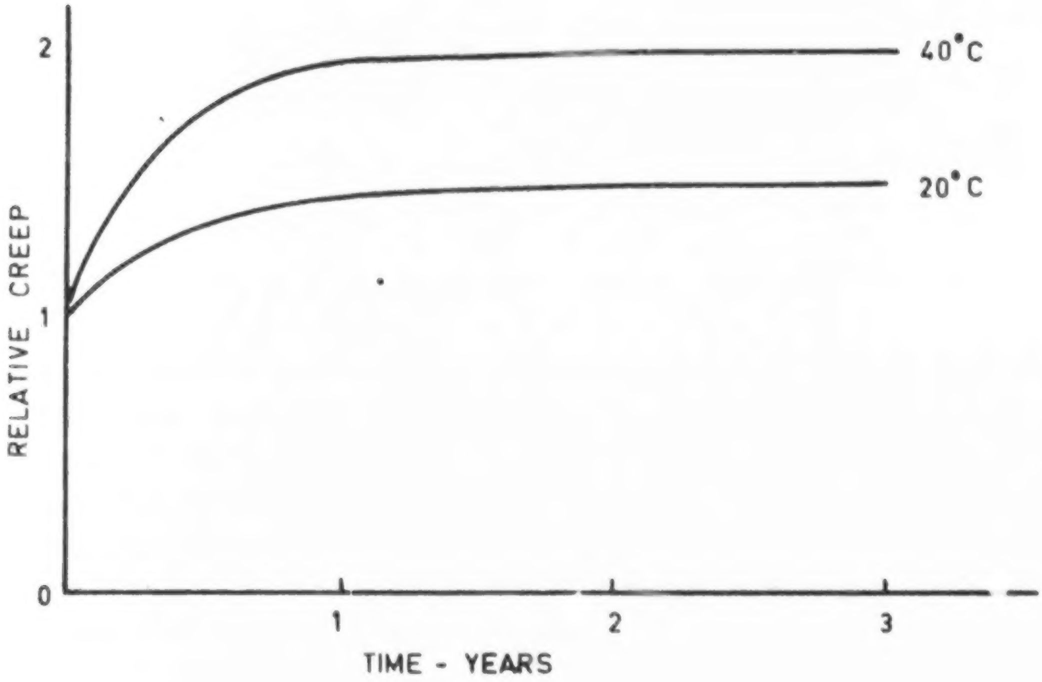

Figure 13. Relative creep in green or dry wood in a constant environment

Some work has been done on creep in wood in compression and tension perpendicular to the grain of the wood, and the amount of creep appears to be slightly greater than that in wood stressed parallel to the grain. After the sustained loads are removed from a wooden member that has been loaded for several years, up to half of the creep is recoverable. The irrecoverable component increases with increasing duration of loading.

Although creep in plywood, at least in bending, appears to be similar to that in solid wood, wood products such as hardboard and particleboard exhibit very much greater creep and in contrast to wood, relative creep in these latter sheet materials increases greatly at increased moisture content levels. The differences in behaviour are probably due to the differences in the nature and degree of bonding of the components of the natural and processed materials. Creep values of between 40% and 500% of the initial elastic deformations have been measured over one month in hardboard and particleboard at moisture content levels from 10% to 18%. Creep behaviour of hardboard, particleboard and wood is compared in Figure 14.

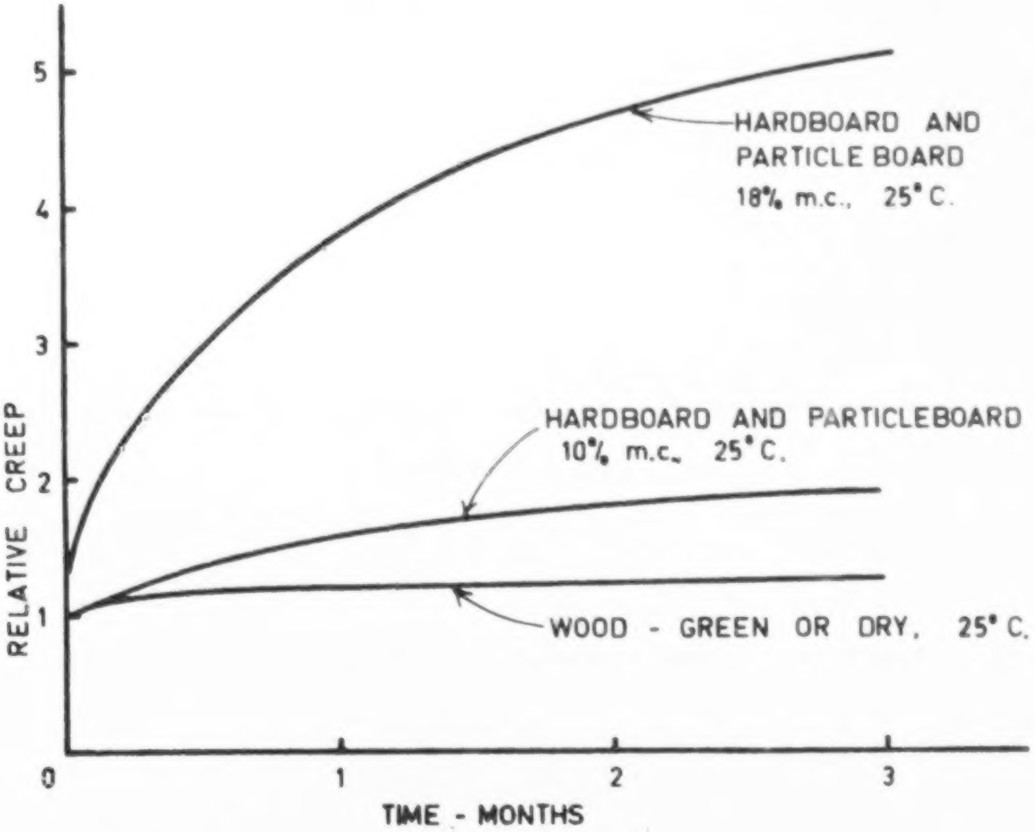

Figure 14. Relative creep in wood, hardboard and particleboard

(b) Stress relaxation

In wood held at constant restraint, the stress in the material diminishes or relaxes at a decreasing rate to about 60% of its initial value, over a period of several months. This phenomenon is illustrated in Figure 15. The rate of relaxation rapidly approaches zero towards the end of that period. The stress relaxation-time curve is similar in shape to the creep-time curve, but its mirror image (see Figure 16).

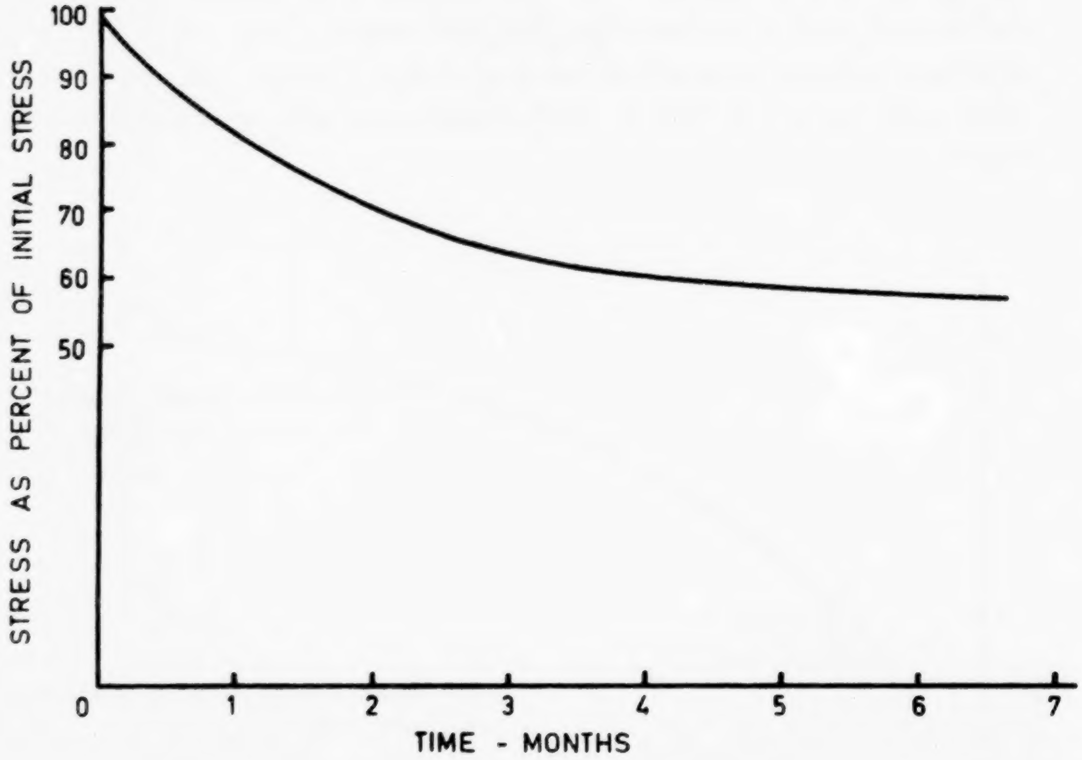

Figure 15. Stress relaxation in wood (green or dry)

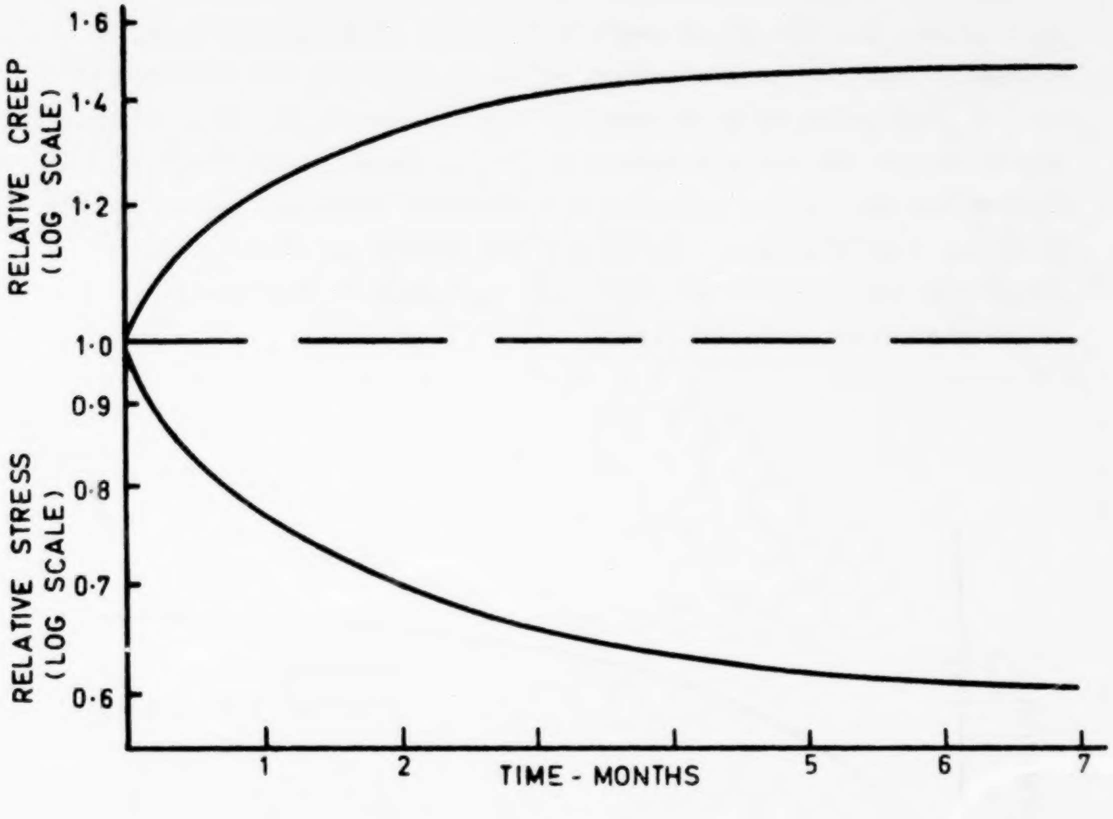

Figure 16. Creep and stress-relaxation in wood in a constant environment

The moisture content of wood does not affect the percentage of stress relaxation, provided the moisture content remains constant. Temperature has a marked effect on relaxation behaviour. No marked effect of stress is evident at stresses below half the short-term ultimate value. Relaxing wooden members can fail if the initial strains exceed about 70% of the average strain at failure in a short-term mechanical test.

The rheological behaviour of wood may be studied by creep or stress-relaxation methods and predictions of either behaviour made from knowledge of the other.

(c) Mechano-sorptive deformation

Although the absolute values of creep deformations in wood are greater at high moisture content levels, the relative creep values, i.e. total deformation at any time expressed as a multiple of the initial elastic deformation, are similar in magnitude in both green and dry wood. An extremely important phenomenon occurring in wood and wood products is that of greatly enhanced deformation that arises during the simultaneous action of applied load and moisture content change. Mechano-sorptive deformation due to the interaction of load and moisture change probably arises in most hygroscopic materials. The behaviour of wood under prolonged loading in a constant and changing moisture environment is illustrated graphically in Figure 17.

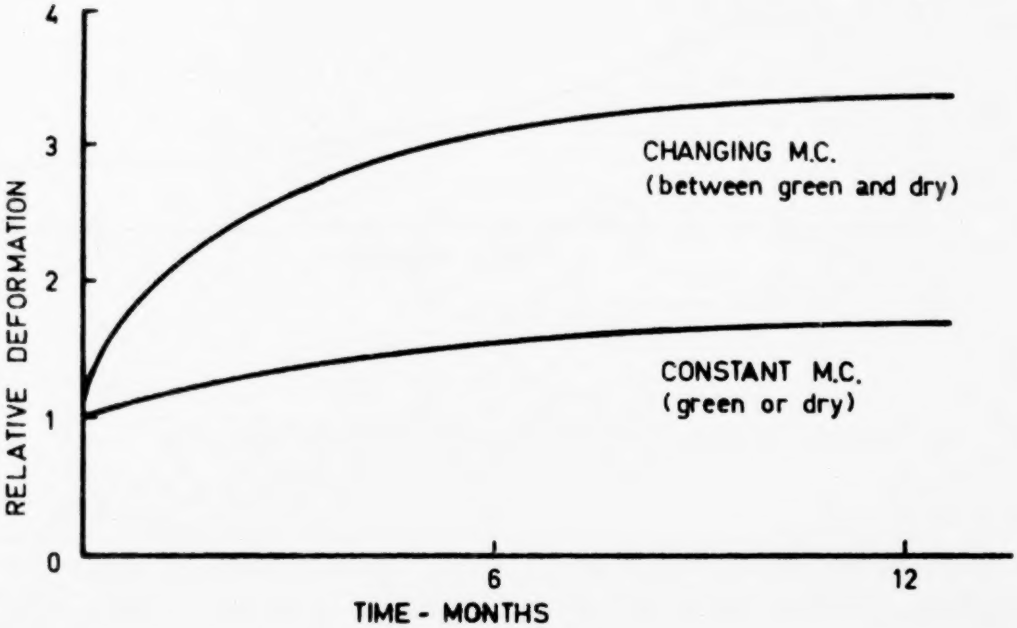

Figure 17. Effect of moisture content change on the relative deformation of wood under sustained loading

When wood under any type of loading is subjected to an initial process of absorption or desorption of water, the deformation due to the applied load increases markedly during the period of moisture content change and the amount of the increase is dependent on the size of the moisture content step. Depending upon the type of loading and the size of the moisture step, the initial deformations may increase by as much as 600% or 700%. In comparison, creep in wood in a constant environment may reach 100% of the initial elastic deformations after several years. The largest mechano-sorptive deformations for a given moisture step arise in wood in compression; intermediate values arise in wood in bending and shear; and the smallest values arise in wood in tension. The behaviour of hardboard and particleboard is qualitatively similar to that of solid wood, but quantitatively the effects are very much greater in the former materials. The quantitative effects in plywood appear to be in between those for solid wood and particleboard or hardboard. Stress relaxation in wood under restraint is increased greatly during moisture changes.

When wood beams, initially at a high moisture content, are subjected to moisture cycling, i.e. alternate processes of desorption and absorption, the deflections increase during all desorption processes, and show little change or small decreases during absorption processes. The resultant effect is a continuing increase in total deflection, as increases in deflection during desorption of water predominate. Failure of the wood can result if the moisture cycling is sufficiently extensive. The mechano-sorptive behaviour of initially green beams drying under load, followed by moisture content fluctuations with climatic changes (or other environmental effects), is shown graphically in Figure 18.

Wood beams, initially at a low moisture content, exhibit deflection increases during the first absorption process and during all desorption processes and exhibit no change or small decreases in deflection during absorption processes subsequent to the first one. Mechano-sorptive behaviour of dry wood during moisture content fluctuations following environmental changes is illustrated in Figure 19.

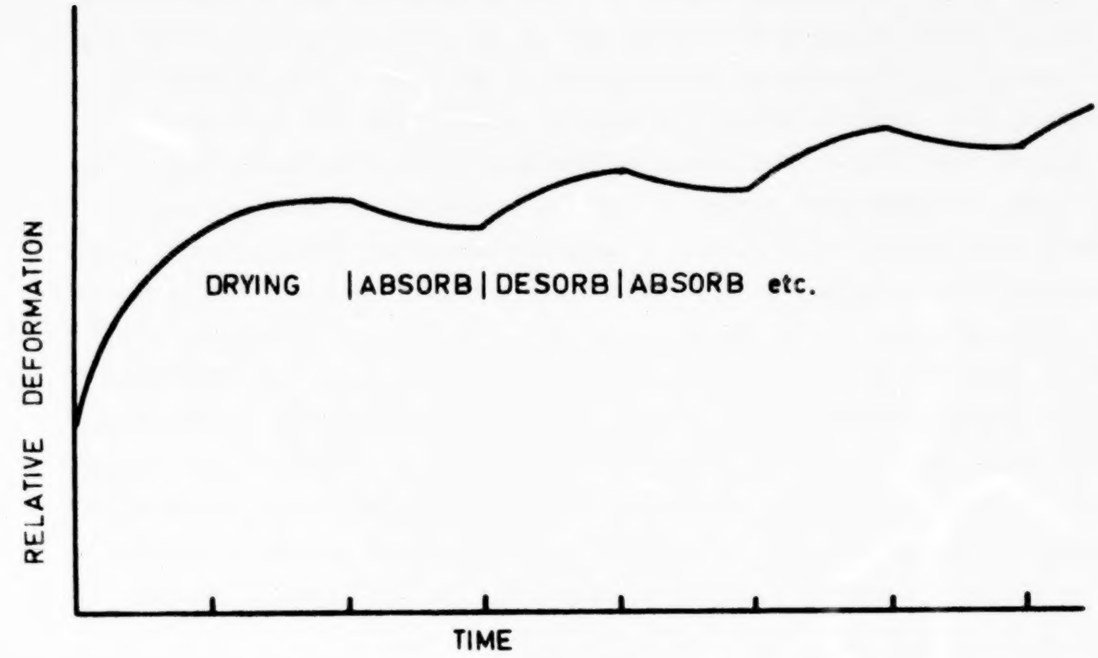

Figure 18. Mechano-sorptive deformation in wood beams drying from the green state, followed by small moisture content fluctuations due to climatic or similar environmental changes

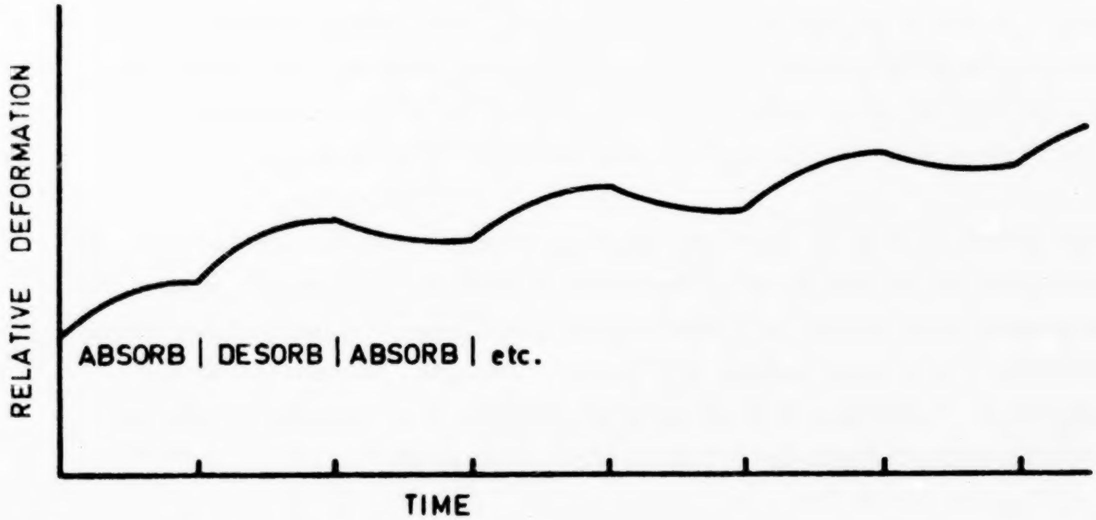

Figure 19. Mechano-sorptive deformation in beams of dry wood subjected to moisture content fluctuations with environmental changes

The magnitude of the increase in deflection is proportional to the magnitude of the change in moisture content and although the rate of change in moisture content affects the rate of change in deflection, it does not affect the magnitude of the deflection. This behaviour is illustrated in Figure 20. The transient effects on deflection are moisture dependent and are not time dependent. The behaviour described has been produced also in very small samples of wood in which cyclic changes in moisture content were induced in a few minutes, and the magnitudes of the effects were similar to those in large samples in which the cyclic changes occurred over periods of days or even months.

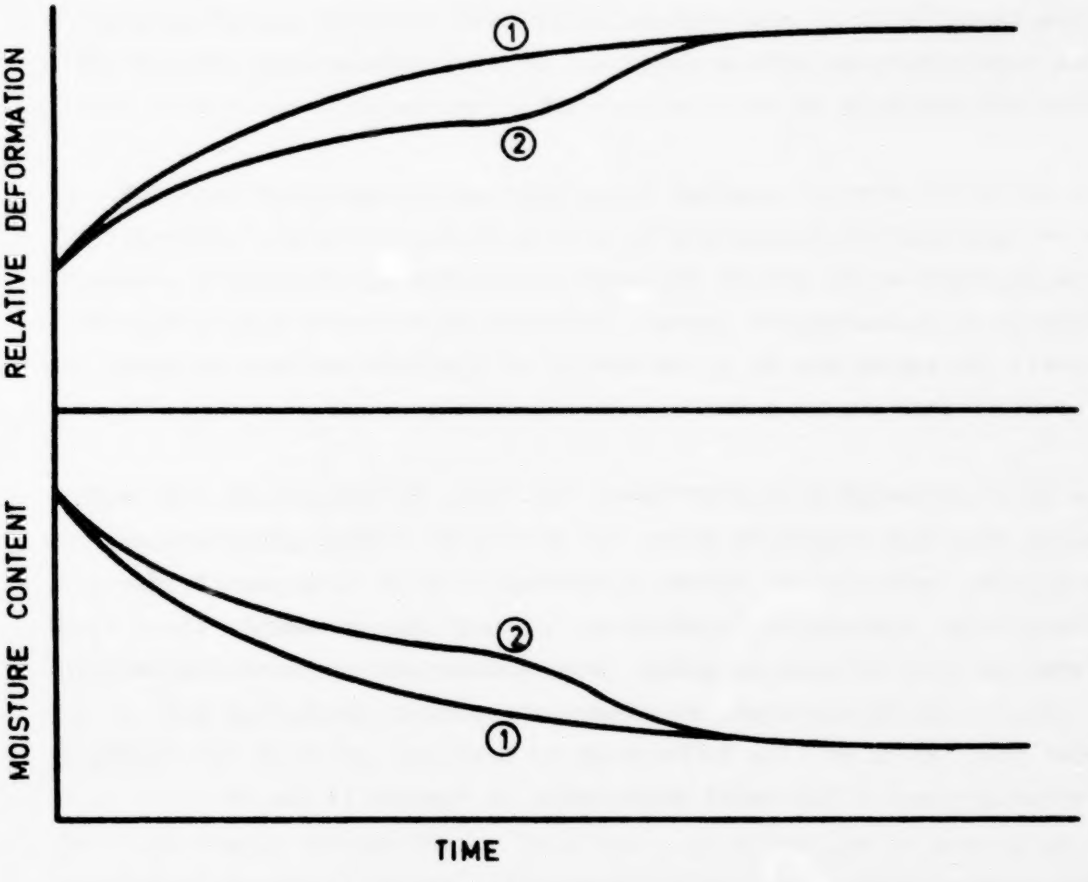

Figure 20. Mechano-sorptive deformation in beams drying at different rates over a similar moisture content step

The phenomenon described cannot be explained simply in terms of swelling deformations, swelling stresses or changes in strength or in Young's Modulus, at different moisture content values; in fact, correction for some of these factors enhances the quantitative behaviour.

In wood species prone to collapse during drying, the mechano-sorptive deformations arise throughout drying from the green state, whereas in non-collapsible species, the deformations occur only during drying below about fibre saturation level. With collapsible hardwoods, mechano-sorptive deformations in structural timbers drying from the green state can reach 2 to 3 times those which occur in non-collapsible hardwoods and softwoods. Considerable reduction of mechano-sorptive deformations in collapsible species can be achieved if the timber is partially dried before installation in a structure, if allowed to dry in the structural frame before service loads are applied, or if given temporary support to reduce the influence of service loads during drying.

In a structure erected in green timber that dries under service loads, the mechano-sorptive deformation occurring during the large, initial moisture decrease may amount to several times the initial elastic deformation. In subsequent years, the structure will continue to deform in small increments due to a combination of creep and mechano-sorptive deformation that occurs annually with climatic changes.

In a structure erected in dry timber, the total deformation is very much smaller than that occurring in an initially green timber structure as there is no large initial change in moisture content with its corresponding large increase in deformation, although the increments in deformations due to time-dependent creep and mechano-sorptive phenomena will be of similar magnitude in subsequent years to those in green timber that has dried. The differences in behaviour of these two types of structure were illustrated graphically in Figures 18 and 19.

Under usual conditions met with in Australia, annual increases in deformations of structures amount to less than 5% of initial elastic deformations, but where abnormal moisture fluctuations arise under indoor or outdoor conditions of exposure, much larger increases in deformation can occur. Moisture fluctuations in timber can be reduced by applying surface coatings or impregnating the wood with water-repellent materials.

In the SAA Timber Engineering Code and in the SAA Timber Framing Code, factors of 2 and 3 have been adopted in stiffness calculations for members in bending and compression to allow for the described effects of duration of loading in dry and initially green wood, respectively. In accepting the factor of 3 for initially green wood, account was taken of the fact that a substantial amount of drying occurs in green timber between the time of processing a log and the time at which service loads are applied to the sawn timber in a structure. Where practical conditions differ from this, increased factors may need to be applied.

The phenomenon of the interaction of load and moisture change in wood may be used to advantage in that moisture changes may be induced in restrained wood to assist in causing desired deformations, e.g. removing distortions from buckled or twisted boards or panels, weighting of timber stacks during seasoning to reduce bow and twist in planks.

(d) Reduction in strength under sustained loading

The strength of wood decreases markedly as the duration of loading increases. In bending, the long-term strength of wood for a duration of loading of about 50 years has been predicted to be approximately 56% of the short-term ultimate strength. The amount of the reduction in strength appears to be similar in both green and dry wood.

In deriving permissible stresses for timber for design purposes, reduction factors are applied to allow for the effects of sustained loading on strength. For example, a reduction factor of 9/16 is used for bending. Where loads will be applied for periods of less than 5 years, the permissible stresses may be increased. The appropriate multiplying factors for various periods of loading are given in the SAA Timber Engineering Code.

The relationship between stress level and time to failure in bending as determined by Wood (1951) is illustrated in Figure 21. Unpublished work by Armstrong (CSIRO) on green, initially green and air-dry wood loaded in bending, compression and shear, confirm Wood's results for bending but indicate significantly greater reductions in strength in compression and shear.

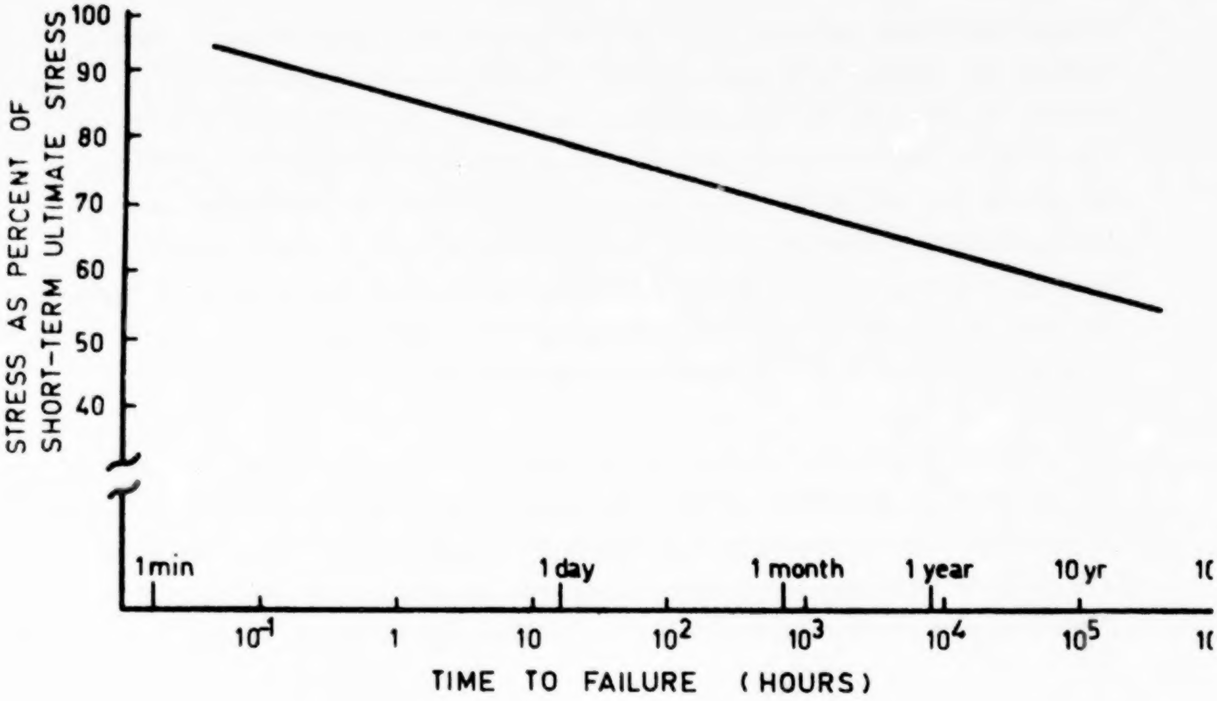

Figure 21. Effect of sustained loading on the strength of wood in bending

The derivation of basic working stresses from the results of mechanical tests and their modification to provide permissible stresses for structural timber will be discussed in further papers.

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CONVERSION OF TIMBER

Mervyn W. Page[1]

To satisfy the world's current needs for forest products approximately three thousand million cubic metres of logs are extracted from forests annually. Most of this wood, in fact a little over half, is consumed as fuel (including charcoal) and most of the fuel is used in domestic situations. Of the remainder, approximately 30% of the total extracted log volume is converted into sawn timber, rail sleepers and veneer, while approximately 18% is employed for such uses as poles, piles, pit props, pulp, particle and fibre board and for tannin and distillation products.

The world production of sawn timber, our particular commodity of interest in this session, is approximately 440 million cubic metres. North and Central America are by far the largest producers of sawn wood, between them accounting for 38% of the total production.

The following table shows the comparative contributions to the total supply made by the various regions of the world.

North and Central America	38% of total
USSR	18%
Europe	18%
Asia	17%
South America	5%
Africa	2%
Oceana	2%.

North and Central America and Europe both export up to 30% of their production. Of the Asian countries Indonesia also exports 30%, while Malaysia and the Philippines export about 60% of their total sawn output.

Approximately 77% of the world's sawn timber supply is obtained from coniferous species, the large producers of coniferous timber being North and Central America, USSR, Europe and Asia. The important producers of sawn hardwood are Asia, North and Central America, Europe, USSR and South America.

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[1] An officer of CSIRO, Division of Chemical and Wood Technology, Melbourne, Australia

The uses for which sawn timber is employed are legion. In the larger sizes, normally up to about 360 mm x 360 mm in section, sawn wood is used in heavy construction, such as bridges and wharves, while in the smaller sizes, usually down to about 70 x 38 mm, sawn timber is probably the world's most widely used structural material for domestic house construction. In between these size limits timber is also used extensively as framing for industrial buildings, in industrial flooring and roofing, in stairways and in similar applications.

But timber is also a major material for use where decoration, as well as strength and stiffness, is required. It is an important material for wall panelling and trim, for furniture and joinery and decorative flooring. Sizes required for such uses are seldom larger than 75 mm thick x 300 mm wide but can be as small as 19 x 12 mm or even smaller.

Clearly then sawn timber must be produced to meet one or other, but sometimes both, of two distinct quality requirements. Timber for structural purposes must be produced to have sufficient strength and stiffness and for many such uses the appearance of the wood is of little consequence. On the other hand for timber intended for decorative uses appearance is the major consideration, but at the same time the pieces must have sufficient strength for the intended end use.

Worldwide there are a confusing number of grades, particularly strength grades, but in actual practice most individual mills produce no more than two to three strength grades and two appearance grades at the one time. However many mills cutting for the general purpose market produce a wide range of sizes and lengths and in some of these mills the output is sorted and graded, according to size, length and grade, into as many as 120 classifications.

The logs from which these timbers are cut do themselves also vary in size, namely in diameter and length. In addition they vary in quality in that they can contain a range of blemishes and defects, the presence of which cannot always be detected from the external appearances of the log. However, the size and location of these defects must be restricted in the final sawn sizes if these are to meet the specification requirements of particular grades.

The aim in sawmilling then is to convert the round tapering cylinder of a log into rectangular pieces of various dimensions, each having a regular cross section along its length, and to do this in such a manner that the growth ring orientation and the location and size of defects in each piece conform to a desired grade specification. In addition the sawing should be efficient in respect to accuracy, speed and saw cut width.

As logs can contain a range of defects that usually become apparent only after sawing has commenced it is not possible to produce every piece to a desired grade specification, particularly at the production tempo of modern industry, and consequently sorting and grading the mill output into the various qualities, sizes and length classifications is required after sawing.

High capacity mills cutting small diameter logs usually have sufficient time per log to saw each log to desired sizes only, and all quality grading is done after sawing. From small logs the range of sizes that can be produced is limited by the small diameter of the log, and such logs are usually processed by higher speed, mass production techniques.

On the other hand, mills cutting very large logs usually have sufficient time per log to produce sizes and grades according to the actual wood quality revealed as sawing of the log proceeds. This practise has become known as "grade sawing" and is the process traditionally employed in mills producing a wide range of sizes from logs larger than about 450 mm diameter.

The main defects that occur naturally in trees, and consequently in sawlogs, and which have an influence on both the conversion process and the utilisatin of sawn timber are:

A. Heart

Heart is the central portion of a log, including the pith and the adjacent wood, that might be defective.

In coniferous species the heart frequently appears quite sound but often this material is of lower density and lower strength than normal wood and is unsuitable for uses where these properties are criteria. In addition the heart region contains a knotty core, even in logs from pruned plantations or from trees that have undergone some self-pruning.

In Australia, heart in softwoods is referred to as pith and in our major plantation conifer, *Pinus radiata*, the pith region usually contains spiral grain, This fibre orientation causes twisting during drying and necessitates special seasoning techniques to produce straight dried products.

In hardwoods the heart region is usually defective, although it may not always appear to be so. The two main forms of heart in hardwoods are:

(i) brittleheart, which is wood near the centre of the tree which has very low impact strength, although it may appear quite sound and

(ii) decayed heart and pipe, which is where the centre of the tree is either decayed or eaten away by termites, resulting in the well known "hollow log"; usually referred to in the industry as a "pipey" log. Although the wood around the outside of the pipe may appear sound it can be either brittle and/or contain incipient decay.

Heart may not always be in the exact centre of a log but can be eccentric and can also wander about the geometric centre of the log along its length.

In hardwoods the "heart" must usually be excluded from sawn products and the sawmilling process must provide for heart material to be discarded out of the sawmill at various stages throughout the milling process.

B. Knots

Knots result from overgrown branch growth contained within the tree being cut across by ripsawing and thereby exposed on the surfaces of sawn timber. Their presence in sawn timber can reduce strength by causing deviations of the grain around the knot and in certain cases by loss of structural section. In addition they can adversely influence appearance, particularly if not intergrown with the surrounding wood.

From the utilization point of view it is important which way the included branch is bisected during conversion. If timber is produced with a back or flat sawn growth ring orientation knots appear on the sawn surfaces as round knots, whereas on the faces of quartersawn timber knots occur as spike knots. Generally, from both strength and appearance points of view, round knots are preferred. This requirement necessitates the conversion process providing a means of rotating the log to a wanted orientation before sawing commences and of turning flitches before subsequent resawing.

C. Bumps

When branches are pruned from a living tree, either mechanically or by the tree itself, the subsequent overgrowth of the branch stub can sometimes be associated with decay. Unfortunately there is no means of determining before sawing commences whether or not decay is present.

The presence of an overgrown branch stub is usually indicated by a swelling on the surface of the log, the size of the "bump" indicating the extent of the overgrowth, but giving no indication whatsoever whether or not decay has taken place. As decay must either be excluded altogether from some products and strictly limited in occurrence in others, the likelihood of the unexpected appearance of decay in a log during sawing requires the sawmilling system to be sufficiently flexible in operation to enable the sawing machine operators to change their production intentions during the conversion process.

D. Pinholes

Pinhole attack is caused by the "ambrosia" beetles, which bore straight holes about 1.5 mm in diameter in green hardwood trees or logs. When the wood dries the beetles die and the infestation ceases. Coniferous species are not attacked.

Unless the holes are very clustered their presence in structural timber is usually not of importance, except where there is decay associated with the pinholes. For decorative timber intended for clear finishing, however, they are often completely excluded, while for timber that is to be painted their occurrence is limited by specification.

Again, unfortunately, the presence and certainly the severity of pinhole attack is often difficult to determine from the external appearances of the log and therefore the milling system needs flexibility of operation to enable the occurrence of this defect in the finished product to be controlled.

E. Gum Veins and Pockets

These occur principally in a number of eucalypts. When susceptible trees are injured, either mechanically or by fire or by intensive insect attack and even sometimes by drought, the trees exude a gum or kino which spreads like a shield over the injured tissue. In conversion this material is revealed as pockets, veins or rings.

Gum is unsightly and not permitted in timber for such uses as panelling, feature flooring or the exposed parts of joinery or furniture, however, small gum veins can be permitted in timber to be painted or covered. In structural applications gum veins and pockets mainly affect shear strength and their size and location must be limited by specifications.

From the conversion point of view logs that contain gum should preferably be converted into backsawn timber. By so doing it is possible to produce some pieces with one face clear of gum, enabling them to be used in the many applications for which only one defect free face is required, such as flooring, panelling and some joinery uses. On quartersawn timber gum would appear on both faces and in addition there is likelihood of corners shelling off.

F. Shakes

Shakes are partial or complete separation between adjoining layers of wood, due initially to causes other than drying. The two most common forms of shakes are

(i) star shakes - due primarily to radial and tangential growth stress gradients throughout the tree

(ii) ring shakes, which are often caused by cambial damage to the growing tree and/or impact loads suffered by the tree during falling. As shakes constitute an actual fracture of the wood their influence in both structural and appearance applications is obvious.

In conversion the aim should be confine shakes to the edges or corners of sawn pieces, so that they can more easily be removed during subsequent processing. This is more easily achieved if the first cuts in a log can be aligned along the major shakes, but unfortunately this is frequently made difficult by each end of the log exhibiting a different shake pattern.

G. Spring

Spring is the longitudinal bending that takes place in both portions of a log or flitch as they are separated by a saw cut, the bending being towards the bark. This type of distortion takes place in most sawlogs when the are sawn. However, it takes place to varying degrees and is not always troublesome. It is almost always more troublesome in hardwoods than in softwoods, in which species it is seldom a problem. In particular it can be very troublesome in small, immature, fast-grown hardwoods.

Spring results from the release by ripsawing of growth stresses in the tree and in severe cases causes wasteful "face cuts" to be made to straighten bent flitches and to reduce thickness variations. It also causes rejection of any sawn timber that is so distorted by spring to be beyond the limits of relevant specifications. This influence of spring on the utility of sawn timber can be substantially reduced if pieces are produced to be backsawn rather than quartersawn. In this way the distortion is exhibited as bow, rather than spring in the finished item, which is then much easier to push straight.

H. Log Taper

As indicated earlier, one of the problems in sawmilling is to convert the tapering cylinder of a log into sawn rectanglar pieces of uniform cross-section along their length. In achieving this saw cuts can be made either parallel to the outside of the log - referred to as taper sawing, or parallel to the longitudinal axis of the log - referred to as parallel sawing. In practice logs may be sawn by a combination of both systems.

Taper sawing is somewhat slower to perform and therefore more costly than parallel sawing, but it results in straighter grain timber which consequently has less tendency to distort during drying, it machines better and has greater stength. Naturally the degree to which these advantages accrue depends on the amount of taper in the log and some logs have such slight taper that little or no advantage results from taper sawing.

Sawmilling

The more common types of equipment used in sawmilling will now be briefy described and any limitations in relation to dealing with the foregoing log characteristics will be discussed.

The primary or green sawmilling process can be divided into four distinct activities:

1. log sawing
2. resawing
3. docking
4. sorting and grading.

1. Log sawing, which usually is the cutting from the log of flitches or other pieces for subsequent resawing to either width or thickness or both, is carried out on machines or combinations of machines usually called "headsaws" or "head rigs".

The most common headrig is a combination of either a band or a circular saw and a log carriage which carries the log backwards and forwards past the saw, enabling a saw cut to be made on each forward travel.

The equipment used to load the log onto the carriage incorporates log turning devices which permit the log to be rotated into the most favourable position for conversion before sawing commences and to be subsequently turned into new positions during processing.

The log is held on the carriage by headblocks, which can be accurately transversed across the carriage so that pieces of wanted dimension can be cut from the log. These headblocks can also be moved independently of each other, permitting the log to be oriented for taper sawing.

Carriage and saw combinations offer a very flexible production system, permitting the opportunity to cope with natural defects as they are revealed during sawing. However, as cutting is sequential even when double cutting saws are used, the system is relatively slow compared with multi-saw machines and is therefore more suited to the larger logs. Sawing speeds seldom exceed 1.5 m/sec.

Carriages vary in degree of mechanisation, from very simple machines on which all adjustments are made manually to large fast machines on which all the operations are controlled remotely. As well as being used in combination with a headsaw carriages can also be used in conjunction with a chipping head, which operates in front of the saw to reduce the outside portion of the log directly into pulp chips.

The machine that offers the highest production capacity, but lacks flexibility, is the high speed gang frame saw. This machine consists of a reciporacting sash which carries a number of saws and through which the log is fed. As sashes can carry twenty or more saws and as log feed speeds can be as high as 0.5 m/sec, productivity can be very high. However, as all cuts are made at the one time, the ability to deal with defects hidden within the log is limited

A third type of machine, which endeavours to compromise between these two extremes is known generically as a log edger. It consists of a means of supporting the log either along its length or at its ends, and moving it between two, and sometimes four, saws.

On simple machines the spacing between the saws are fixed and the logs are passed through the machine once only. On the more advanced designs the log can be reciprocated backwards and forwards between the saws, the spacings between which can be rapidly and accurately altered between sawing passes. On the very latest machines chipping heads are located in front of the saws, which can be either circular or band.

Log edgers,particularly the two saw machines, offer some of the production flexibility of a sequential sawing system coupled with some increased productivity, due to the use of multiple saws. In material prone to spring excessively log edge **edgers overcome the problem of face** cutting, but like the gang frame saw, they saw parallel to the longitudinal axis of the log, unless the saw is oriented to taper saw on one side of the log only. In some circumstances this may have some advantages but it also has the disadvantage that the other side of the log is then sawn directly against the taper.

2. Resawing

Resawing is the sawing to width or thickness or both of larger pieces produced by the log sawing machines.

The most common type of resaw consists essentially of a horizontal table in which is arranged either a single circular or a single bandsaw. The table also incorporates a fence or gauge, which is parallel to the saw line and which enables wanted timber dimensions to be produced by setting the gauge the desired distance from the saw line and causing the timber to be pressed against it while being passed through the saw.

On the simpler machines the feed of the timber is either fully powered or at least power assisted and the timber being processed is passed backwards and forwards across the bench, only one piece at a time being handled. On higher production machines flitches, after passing through the saw, are returned to the infeed side of the bench by a system of transfers or conveyors, permitting another piece to be sawn while one is being returned.

As cutting is sequential a high level of production flexibility is achieved, but production capacity is relatively low. Capacity can be increased by employing two, three or four saws, but some flexibility is sacrificed.

Small carriage and saw combinations are sometimes used as resaws and offer much the same advantages and disadvantages as the resaw benches just described, except that they can be less labour-intensive.

Reciprocating gang framesaws are widely employed as resaws, giving very high production capacities, but, of course, at reduced flexibility. However, where flitches for resawing can be prepared to a reasonably high quality, this reduction in grade sawing ability may not necessarily be a disadvantage.

Multi-saw ripping machines are also classified as resaws, but are used mainly for cutting timber to desired widths. Such machines carry from two up to about twenty circular saws, the spacing between saws or on the larger machines between banks of saws, being capable of accurate variation between cuts.

3. Docking

Docking is the cross-cutting of sawn pieces to produce either wanted lengths or to upgrade the product by removing defects. Where the intention is to produce ordered lengths or to simply square uneven ends the process is sometimes referred to as trimming.

In low capacity mills the sawn timber is simply conveyed lengthwise past an operator who, after deciding what cuts are necessary, controls a single cross-cut saw, either manually or by power. Such systems handle an average of two to three pieces per minute.

At the other end of the scale, in large modern mills the sawn timber is conveyed transversely past graders, who after deciding what cuts, if any, are needed key this information into a computer. Subsequently the timber is conveyed, also transversely, either under or over a large bank of circular cross-cut saws, which under the command of the computer perform the cross-cutting pattern decided by the grader. By comparison these systems can handle an average of up to sixty sawn pieces per minute.

4. Sorting and Grading

After having been produced to wanted cross-sectional dimensions, lengths and grades, the sawn timber must then be prepared for marketing by sorting either into these classifications, or into orders, although in many cases timber is seasoned and/or machine profiled before sale.

In small mills the grading and sorting is carried out by the dockerman and is then manually stacked, often by the same operator.

In medium-sized mills the timber is conveyed past grading and sorting personnel by either transverse conveyors or on a circular table and from which the personnel manually build stacks of the timber they classify. Otherwise graders place classified timber into a series of channels, along which it is conveyed on edge, each channel leading to a stacking area for one particular sort of product.

For the larger, high capacity, mills computer controlled sorting systems are available in which sawn timber is moved transversely past equipment which measures and records its physical dimensions in a computer. A grader then inspects both sides of the piece, and keys the appropriate grade into the computer. The piece is then conveyed over a series of storage bins, each holding a particular classification. As the sawn piece passes over the bin appropriate to its classification the computer causes it to be deposited into that bin. Bins, when full, are emptied automatically and the timber made up into stacks of sorted and graded wood.

The above descriptions are, by intention, very cursory and are intended to provide timber users with a general understanding of some of the production philosophies, the problems and the manufacturing systems associated with the conversion of forests into sawn timber.

SEASONING OF STRUCTURAL TIMBER

F. J. Christensen[1]

INTRODUCTION

In general, structural timber should be dried to an extent determined both by its required load carrying capacity at time of installation and its subsequent tendency to develop unacceptably high levels of drying degrade in terms of structural or aesthetic considerations. Partial drying and possibly some redrying may be required for timber needing preservative treatment to combat high biological attack hazards in service. These guidelines apply to both sawn and round structural timber which can generally be dried by the same methods and equipment.

Drying improves the physical properties of timber and its general performance in service. In the present context, specific advantages of dried over green (undried) timber are: its reduced (a) mass, (b) cost of transporting, (c) tendency to creep under load, (d) susceptibility to biological decay and (e) capacity to develop severe drying degrade with possible loss of strength; and its increased (a) strength, (b) dimensional stability, (c) capacity to absorb preservative liquids during pressure treatment and (d) its ease of handling. Within certain specified limits, the extent of these improvements depends directly on the size of the moisture change: the lower the moisture content, the greater the benefit.

The drying of timber can be complicated by the large diversity of species which are or could be used for construction in countries utilizing tropical forests for timber supplies. Problems also arise from adverse effects of tropical climates especially during monsoonal periods when the potential for air drying is drastically reduced.

TIMBER DRYING PRINCIPLES

It is assumed that workshop participants now have an idea of the composition and structure of wood: the basic differences in structure between hardwoods [pored timbers] and softwoods [principally conifers] in terms of such structural elements as tracheids, vessels, fibres, cells, lumens, pits and rays; the major chemical components common to all woods; the distinction between sapwood and heartwood; the existence of growth rings consisting of early wood and late wood bands; the presence of deposits of various materials in the inactive cells of the heartwood; and the occurrence of growth stresses, reaction wood, spiral grain and corewood (juvenile wood). All of these factors influence the drying of wood and its subsequent appearance in one way or another.

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[1] An officer of CSIRO, Division of Chemical and Wood Technology, Melbourne, Australia.

Moisture content of wood

Water is a major component of wood, often accounting for more than half of its total mass in the green (undried) state. Its removal, either partly or almost completely, is the principal objective of the timber seasoning or drying process. The amount of water in wood or its moisture content is expressed as a percentage of the oven dried mass of the wood substance:

$$\text{Moisture content (MC)} = \frac{\text{Mass of water in wood}}{\text{Mass of oven dried wood}} \times 100\ \%$$

There is a great deal of variation in green moisture content both within and between different species of timber and even in different parts of individual trees but most values range from 50-150%.

Optimum drying of structural timber

The amount of drying ideally needed by timber before using it in a structure can vary greatly: from virtually no drying at all in some cases to partial or complete drying in others.

During drying, all timber shrinks to a greater or lesser extent. It may also develop degrade in the form of splitting, checking and distortion (cupping across its width; and twist, spring and bow along its length). Provided strength requirements are met, the amount of drying required then depends on how much shrinkage and degrade occur and how much can be tolerated in relation to how and where the timber is used, i.e. whether in an exposed position where appearance is important or, if in a concealed position, whether any subsequent distortion creates additional work at a later stage of building or makes some aspect of the structure unsightly as (further) drying out occurs in situ.

In passing, all timber mouldings (flooring, architraves, skirtings, etc.), joinery timbers (principally door and window frames, and window sashes), doors and cupboards should preferably be thoroughly dried before being installed in a building.

Equilibrium moisture content

If left for sufficient time, wood will come to a moisture content in equilibrium with the psychometric conditions [dry bulb temperature (DBT) and relative humidity (RH)] of the air to which it is exposed. This value is called the equilibrium moisture content (EMC) of the wood. If wetter than the corresponding EMC, the wood will dry out to that value; if drier, it will absorb moisture from its surroundings to increase to the EMC value.

Extreme values for EMC range from about 5-25% mainly depending on the country and its climate, but occasionally on extraneous factors such as leaking plumbing and inadequate ventilation under buildings on wet soils. The lower end of the EMC range occurs in very cold and/or very dry climates such as in polar, desert or dry inland regions. The upper end occurs in very wet climates where the relative humidity remains high for prolonged periods. In most countries, the EMC is not just a static value but one which varies to a fairly limited extent throughout the year in accordance with the prevailing atmospheric conditions in different parts of a country.

In most tropical regions, the EMC can be high as 18-20% near the coast during the moonsoon, then falling perhaps to 14-16% during the drier parts of the year. In temperate regions, a yearly variation of 9-15% is common. In dry desert regions, values are likely to be as low as 5-6%. For air conditioned buildings, the EMC is commonly about 8% when both DBT and RH are strictly controlled (with refrigeration units) and anyone's guess when they aren't.

It is important to stress that it takes a finite time for wood to reach

EMC depending principally on its MC and thickness, and the size and duration of the change in atmospheric conditions to which it is exposed. This could vary from a few days for thin timber subjected to a small change in EMC conditions to years for large sections of dense timbers at high moisture contents.

The practical result of changes in EMC on dry timber used in structures is their influence on its dimensional stability i.e. the amount of shrinkage and swelling that occurs mainly in the width and thickness of components. Although relatively slight in most cases, these periodic changes in EMC can cause doors and windows to expand and stick during the wetter parts of the year or unsightly gaps to develop in a variety of timber objects during the drier periods.

Fibre saturation point of wood

The fibre saturation point (FSP) is a useful concept in drying. It is the hypothetical moisture content at which all of the free water in the cell lumen or cavity has been removed while the cell wall is still saturated with water. The value of FSP varies from about a low of 22% to a high of about 33% for different species. At FSP, certain wood properties begin to change: e.g. normal shrinkage commences and most strength properties start to increase, two factors of direct interest to the structural engineer.

Shrinkage of wood

Green wood starts to dry from the outside inwards, since moisture flows from a region of high to low concentration. Therefore, at all stages of drying, there is a gradation of MC varying from the current EMC value right at the surface to the maximum MC in the interior of the wood. In the early stages of drying, the establishment of such a moisture gradient indicates that part of the wood is already below FSP and has started to shrink and that part is still well above FSP and has not started shrinking. Thus, changes in the external dimensions of the wood start when its average moisture content is still above FSP.

Normal shrinkage is usually expressed as the percentage change in green dimension of the wood from green to 12% MC. From about FSP, shrinkage increases linearly with decreasing MC until the wood is almost oven dry. Individual values are given for tangential and radial shrinkages which are roughly in the ratio 2:1 respectively. Values are sometimes given for the unit shrinkage, i.e. the percentage change in shrinkage per 1% change in MC. Unit shrinkage is used for estimating changes in dimensions between 5-25% MC.

Wood does not shrink evenly in the longitudinal, tangential and radial directions. Mostly, the longitudinal shrinkage is negligible (<0.1%) and can be ignored but not when spiral grain is present. Normal shrinkage values for most species, from green to 12% MC, would be covered by the range 2-8% tangentially and 1-4% radially. Thus, the way in which a piece of timber is sawn determines how much it shrinks in width and thickness. As mentioned later, it also influences the type of drying degrade that occurs. The shrinkage in width of backsawn [flatsawn] timber is greater than that of quartersawn [edgesawn] timber of the same width, though the reverse is true in respect of shrinkage for equal thicknesses.

With some species, notably many species of the genus Eucalyptus, an abnormal form of shrinkage known as "collapse" occurs in the green wood down to FSP. Collapse has certain characteristics that make it easily recognizable such as drying checks that pinch-in at their edges, a general concavity of the faces or edges of a piece of timber or "washboarding" of its faces, and the occurrence of end checks in the early wood. Shrinkage due to collapse can be of the same order of magnitude as normal shrinkage, but is usually somewhat less. Much of it can be recovered by a steaming treatment known as "reconditioning". This is most effective when given at an average MC of 20% or less, a value which generally ensures that all parts of the wood have dried below the FSP and all collapse shrinkage has taken place.

Drying degrade, stresses and distortion

The occurrence of drying defects and the worsening of inherent defects in wood can usually be traced to the influence of shrinkage and its effect on the development of drying stresses. The strength property that determines the susceptibility of wood to checking and splitting during drying is its tensile strength perpendicular to the grain.

In the early stages of drying, wood at or relatively near the surface (the case) falls below FSP and wants to start shrinking but this tendency is resisted by the wetter, unshrunken wood in the interior region (the core). As a result, the case goes into tension and the core into compression. If the drying from the surface is too rapid and produces a steep moisture gradient, the shrinkage stress produced in the case may exceed the transverse strength of the wood and produce a fissure in the form of a split or check. This usually continues to worsen with further drying of the case until the core MC starts to fall below FSP and the established stress condition starts to reverse.

At this stage of drying, the case has largely dried to EMC and most of its shrinkage has occurred. From then on, the core progressively dries and wants to shrink but is restrained by the already shrunken case.This places the core into tension and the case into compression. If the shrinkage stress in the core becomes too high, then internal checking will occur. At the same time, the compressive forces exerted on the outer part of the wood may partly or fully close the surface checks and even narrow any splits near the surface. This is the normal condition after drying and is commonly known as case-hardening (not a good term, being dissimilar to case-hardening of metals). It can be relieved by a mild steaming treatment or a high humidity treatment (HHT) aimed at putting some moisture back into the case and relieving the drying stresses.

Moisture gradients in timber can lead to distortion if such timber is deep sawn or unevenly dressed after drying. For this reason, timber should be converted as near as possible to the final cross section required before drying is commenced.

Factors affecting drying rate

The three principal factors that affect drying rate are the DBT, RH and the velocity of the air passing over the timber in stickered stacks. These are commonly called the drying conditions. Increasing the DBT increases the rate of diffusion of moisture from the interior to the surface of the timber. Decreasing the RH and increasing the air velocity both increase the rate of evaporation of moisture from the surface of the timber. These principles apply irrespective of whether timber is air dried under natural conditions or is dried under accelerated conditions in some type of drier.

With all other factors equal, drying rate is also affected by: the MC of the timber (the higher the MC, the easier it is to remove the moisture); the permeability of the timber (the higher the permeability, the higher the rate of diffusion); the structure of the timber (non-pored timbers have higher permeabilities than pored ones); the thickness of the timber (the thicker the timber, the longer it takes to dry); the density of the timber (the higher the density, the slower the drying); width of stack (the wider the stack, the greater the lag in drying at its centre); sticker thickness (the thinner the sticker, the slower the drying within limits); method of sawing (backsawn timber generally dries faster than quartersawn timber).

Drying schedules

A drying schedule consists either of one fixed set of drying conditions or a series of progressively more severe drying conditions determined by the reducing MC of the timber.

It is usual to give schedules in terms of DBT and wet bulb temperature (WBT) or wet bulb depression (WBD = DBT - WBT). Measurement of WBT in preference to RH (which can be obtained from DBT and WBT readings) is based on (a) the better accuracy and reproducibility attainable with WBT measurements (which are also not subject to the upper DBT limitations of RH measurement) and (b) the unique relationship between WBD and EMC over the normal range of kiln temperatures (which gives a ready indication of the severity of the drying conditions being applied).

TIMBER DRYING PRACTICES

Stacking and handling

Stacking: Good drying results depend to a large extent on good stacking practices, irrespective of the method of drying used. The main purposes of stacking are (a) to provide uniform air circulation over the timber with the aim of promoting uniform drying conditions and (b) to minimize drying degrade due to distortion and checking. Different thicknesses of timber should not be dried in the one stack but this can be done with groups of species having similar drying characteristics.

One of the first questions to decide with the introduction of drying operations is the optimum stack size(s) to use, particularly if the use of driers is contemplated. Stack size must also be considered in relation to the lifting capacity of any mechanical handling equipment used for moving stacks about the seasoning yard.

Widespread experience has determined that stack widths and heights of from 1.6 to 1.8 m are optimum at most drying plants not employing mechanical stackers. Optimum stack lengths are more difficult to determine but are obviously related to the lengths of timber produced and the length of any driers used. The best decision is to use only one stack length or, failing that, the very minimum of stack lengths. Different lengths of timber can be accommodated in the one stack in several ways depending on their actual length. If longer than half the length of the stack, then alternate pieces across each layer are end-for-ended to give two square ends to the stack. Suitable spaces can be filled with shorter lengths. Timber should not be allowed to overhang the ends of stacks. The volume of timber in stacks commonly varies from 70-100% of the theoretical holding capacity.

Separating stickers placed between each row of timber are usually 40 x 20 mm in cross-section for general use. They are spaced along the length of the stack at 400-900 mm centres, depending on the thickness of the timber. Stack bearers 100 x 75 mm in cross-section are placed under each row of stickers. Any variations in the thickness of stickers or timber can introduce distortion in the timber from lack of adequate restraint. Stickers must be kept aligned vertically to properly support the timber. The use of simple stacking guides can facilitate and improve stacking practices.

Handling: There are a number of mechanical handling systems in use in seasoning yards. Any system has to meet one or both of two criteria: (a) handling of stacks in the yard and (b) transferring stacks in and out of driers and steaming chambers. For yard handling, the choices are: (a) forklift truck, (b) straddle truck, (c) overhead or gantry crane and (d) mobile jib crane. For drier handling, there are two choices: (a) lift and transfer truck system and (b) drier or bogey truck system. The use and selection of handling systems cannot be treated adequately here.

Appropriate methods of drying structural timber

There are many ways of drying structural timber ranging from simple air drying to sophisticated kiln drying methods. Where a choice of drying method does exist, the determining factors are almost always (a) the cost of drying (including wastage from excessive degrade), (b) the final moisture content required, (c) the period of time available for drying and (d) the appropriateness of the drying technology in relation to the state of development of the country's timber processing industry.

The most appropriate methods of drying structural timber are considered to be:

- Air drying
- Forced air drying
- Predrying
- Kiln drying in:
  - Screen,
  - Solar,
  - Progressive and
  - Conventional kilns

Each of these methods, together with an outline of the equipment needed, will now be considered.

Air drying

This is the simplest method of drying, requiring the very minimum of infrastructure. However, capital investment in timber stocks can be high, particularly for slow drying structural size timber. For 40-50 mm thick hardwoods, drying from green to 15-20% MC can take from 3-24 months or more depending on the species and the atmospheric conditions.

Good air drying rates can be achieved during the drier months of the year in well designed and maintained drying yards exposed to favourable winds. Basic requirements are an open, flat and well-drained site with roadways traversable throughout the year if mechanical handling equipment is to be used. It is recommended for fastest and most uniform drying that stacks be oriented with their length in the prevailing wind direction (not across it).

Good stack foundations are needed to provide adequate structural support for the stack. Otherwise, any irregularities in foundation levels may be reflected in every piece of dried timber from the stack. Foundations are commonly of pier and beam construction with a recommended clearance of 400-500 mm from the ground to the bottom layer of the stack. Piers should be of durable or treated timber, and beams stiff enough to carry the stack-supporting cross bearers without undue deflection.

Side and end gaps must be allowed between all stacks in air drying yards to provide for adequate air circulation through the stacks. For short, low stacks up to about 5 m long and 1.6-1.8 m high, side and end gaps of at least 600 mm are recommended. For long stacks of the same height, the side spacing should be at least 1 m with an end spacing of 1.5-2.0 m. A much wider space is needed every second or fourth row of stacks if handling is by forklift truck or mobile crane. In this situation, two or more stacks may be piled on top of one another to minimize infrastructural requirements. For such stacking, the side spacing should be 1.5-2.0 m and the end spacing 2.0-2.5 m. Spaces between and under stacks should be kept clear of weeds, scrap timber and other debris to ensure that free circulation of air is not impeded in the lower part of the stacks.

As mentioned earlier, air drying rates are markedly reduced by unfavourable weather conditions, e.g. during the moonsoon when RHs are high and timber in unprotected stacks is subjected to repeated rain wetting. Stack covers may help to alleviate the latter problem and decrease the otherwise required drying time to some extent.

The minimum MC attainable with air drying is determined by the EMC of the atmospheric conditions, which can vary considerably throughout the year. Also, rate of drying becomes progressively slower as the wood approaches the EMC value. These factors may not present any difficulties for timber that does not have to be dried to a relatively low moisture to stabilize it sufficiently for satisfactory use. But it does mean that some additional drying, at least at a slightly elevated temperature, will be needed by timber required at MCs lower than the EMC value. Another disadvantage of air drying is the potential economic loss from drying degrade, predominately in the top layers of uncovered stacks and in the outermost boards along both sides of stacks.

In spite of the problems, air drying is widely practised in many countries and gives a generally acceptable result for some if not all of the time.

Forced air drying

This method employs either mobile fan units placed between two or more covered stacks in an air drying yard (yard driers) or fixed fans installed in one wall of an enclosed shed holding stacks of timber. In both cases, the fans draw ambient or heated air over the timber. An air velocity through the stack of 0.5-1.0 m/s is generally used. For the shed units, more even circulation is obtained by sucking the air through the stack. The fans can be automatically stopped by a hygrostat control when the RH rises above about 90% or falls below about 40% (if the timber is susceptible to checking).

Forced air drying is probably no faster than conventional air drying when natural drying conditions are good. It can be much faster when natural drying conditions are poor. Therefore, forced air drying minimizes variations in drying rates caused by seasonal fluctuations in climate. This can reduce both timber stock holdings and the amount of drying degrade produced by conventional air drying. Capital equipment costs are comparatively low and direct operating costs depend on usage and cost of energy used. With forced air driers, mixed species and different thicknesses of timber can be dried in separate stacks at the same time.

Predrying

A predrier is a large, multi-line unit having a single air circulation and humidification system. Heating of the air may be provided from a single source or supplemented by reheating at one or more lines in the drying chamber. For hardwoods susceptible to checking and collapse, drying conditions are usually mild and kept constant at all times (40°C DBT, 2-3°C WBD). More severe conditions could be used for less sensitive timbers. An air velocity of 1.5 m/s through the stack is optimum for hardwoods. Predriers have been built with timber holding capacities of up to 500 m^3.

Predriers are frequently used ahead of kilns to reduce the MC of timber to 20-30%, particularly where natural air drying conditions are poor for all or part of the year. They can also be used as driers in their own right, either for green or partly air dried timber. The mild drying conditions enable different species and thicknesses of timber in different stacks to be dried at the same time. The main problem with this practice is the logistical one of keeping track of the progress of drying of individual stacks.

Capital cost is considerably lower than for kilns and so is the operating cost for drying timber from green to about 30% MC. Below that figure, the position changes on account of the much slower drying rates attainable with predriers. As steam is not essential for heating and humidification, the high capital and operating costs for steam plant can be avoided. Heating can be effected indirectly by filtered exhaust gases from wood residue burners and humidification by atomized water sprays.

Predriers are of greatest interest to the larger producer of structural timber wanting to maintain constant production rates throughout the year and to have the facility to dry to comparatively low MCs as required.

Kiln drying

Distinctions between screen, solar, progressive and conventional kilns are of degree rather than kind. They do differ considerably in capital cost but this is probably little more than a reflection of their differing drying capacities.

Screen kiln: The main aims of this CSIRO design are to keep capital cost low and to simplify the manufacture and packaging of all components for ease of assembly in the field. Mounting all heavy equipment at ground level, including the single air circulating fan, enables lightweight and well-insulated wall and roof panels to be used if desired.

The reversible fan is mounted at the back of the drier adjacent to the heater and humidifying spray. The air is discharged into plenum chambers on each side of the stack, entry to which is through screens extending from floor to ceiling and from end to end of the kiln. The function of the screen is to give uniform air velocity through the stack by providing constant resistance to air flow out of the plenum. Maximum internal lengths are limited to about 13 m by air flow considerations.

Screen kilns have performed well with both hardwoods and conifers. They can be operated over a wide range of DBTs and can be heated either directly or indirectly. Holding capacities range up to about 20 m^3 of timber.

Solar kilns: These can take a variety of forms but all share the common feature of deriving much or all of the heat needed for drying from the collection of solar radiation. They have great potential in tropical and even sub-tropical regions where insolation rates are high throughout the year and not unduly diminished by cloud.

The two main types of solar kilns are based on heating being provided either by the greenhouse effect or by external solar collectors. The latter may also incorporate a rockpile or other type of thermal storage unit to store extra heat collected during the day for use at night. Without stored heat, solars kilns are virtually limited to running during daylight hours only or, at best, until the RH of the air inside it builds up to 90% or so. For both types, it is important to minimize heat losses with adequate insulation.

The timber roof and wall framing of a greenhouse-type unit may be covered on the exterior with sheets of glass or fibreglass reinforced polyester (either flat or corrugated). Clear polyvinyl chloride film can be fitted to the inside of the framing to provide an insulating gap. Slightly raised wooden floors above a well drained base covered with an impermeable membrane minimize loss of heat through the ground. Flat black paint applied to all surfaces exposed to sunlight within the kiln helps to maximize absorption of solar heat by the structure. Drying in a solar kiln is much more effective if (a) there is positive, not just natural, air circulation through the stacks of timber (a screen kiln type system is very suitable for this purpose) and (b) provision is made for venting small amounts of moisture laden air from the kiln.

Solar kilns employing external collectors have tended to be designed like conventional kilns in respect of both the structure and the mechanical components. Thus, capital cost will be comparatively high, particularly when a heat storage unit is included. This will be reflected as a major indirect operating cost (interest and depreciation charges) on account of the relatively small throughput of such a kiln. At the same time, direct operating costs will be relatively low.

Compared with air drying, solar kilns can (a) provide reasonably good drying conditions and relatively constant output throughout the year, (b) reduce drying times by up to half, (c) reduce drying degrade and (d) dry below the prevailing EMC. They are most useful for drying from FSP to EMC or below, since the DBT inside the kiln can rise by as much as 25°C above ambient temperature. Drying times from 30% to 15% MC vary from 6 weeks for 50 mm thick medium density hardwoods to 8 weeks for 40 mm thick dense hardwoods. Solar kilns have been built with holding capacities of up to 40 m^3.

Progressive kiln: In the CSIRO version of this type of kiln, the stacks of timber are loaded end-to-end and are moved progressively through the drying zone on a stack-by-stack basis from the "cold" (or wet) end to the "hot" (or dry) end of a long tunnel-like shed up to 60 m long. Stacks are usually mounted on kiln trucks or bogies but can be moved through the kiln by alternative means. Heated air is sucked in at the hot end by a fan installed to one side of the kiln at the cold end. Hinged baffles placed at regular intervals along both sides of the stacks direct the heated air through each stack in turn from the hot to the dry end. An air velocity through the stack of 0.5-1.0 m/s is ideal

As designed, this kiln is intended to operate at a constant heat input from an oil or gas burner although suitably filtered exhaust gases from a wood residue burner could be used equally as well. The hot gases mix with the incoming air and heat it by more or less a fixed amount above the ambient temperature. To recover as much heat as possible for drying, the air should exit from the kiln somewhere below ambient temperature, preferably close to saturation. For difficult to dry hardwoods, the ambient air should only be heated by 10-15°C. This ensures that drying conditions at the wet end are mild and unlikely to cause checking or other degrade in the greenest and most sensitive timber. If drying degrade is unlikely to be a problem, then larger increases in the temperature of air entering the drier could be used to accelerate drying, but this may be wasteful of energy sources that have to be bought.

Apart from routine moisture measurements, very little skill or supervision is needed to operate this kiln satisfactorily. Its basic simplicity ensures that construction is straightforward and little maintenance is required. Drying times of 5-8 weeks to about 15% MC are fairly normal for green and moderately dense hardwoods 40-50 mm thick. A kiln designed to hold six or so stacks of such timber would be capable of producing a stack of dried timber a week. Higher outputs would best be achieved by building additional kilns rather than by increasing the length of a kiln. This avoids complications with drying and gives greater flexibility with drying operations.

Conventional kilns: Several basic designs for compartment kilns have evolved over the years but wide experience shows that a well-designed cross-circulation kiln is most capable of providing consistently good drying results. Such kilns may be purchased as prefabricated units or constructed on site to set specifications. Aluminium covered panels are commonly used on prefabricated kilns and are generally satisfactory if treated with proper care. Steel sheeted panels are not suitable for hardwood drying because of the possible risk of corrosion. A wide range of materials are satisfactory for on-site construction: reinforced concrete, clay bricks, hollow concrete blocks, or timber or metal frames with various lining materials. Good insulation is essential to prevent heat losses at the higher operating temperatures used in these kilns.

As compartment kilns generally cost much more than the other types of driers already discussed, it is important to use them to their best advantage. For most hardwoods, particularly in structural sizes, it is plainly uneconomic to use an expensive kiln for drying from the green condition when the job can be done just as well and as quickly by a cheaper machine such as a predrier or a progressive kiln. One of the main functions of conventional compartment kilns is the final drying of hardwood already at FSP or below but needed for use at a somewhat lower moisture content. They are sometimes used for fast drying of permeable timbers from the green condition.

Compartment kilns should have cross-shaft fans, mounted above or below the stack, or other fanning designs of proven comparable performance. This is to ensure that the best opportunity is provided for achieving uniform air circulation throughout the kiln, a basic requirement for even drying of timber. Longitudinal shaft kilns are not recommended because they often fail to meet this criterion. The air velocity through the stack should be 1.5-2 m/s. This cannot be achieved unless baffles are provided to restrict or prevent by- passing of air around stacks. Uniformity of drying also depends on achieving an even distribution of temperature and relative humidity in the kiln.

Although it is generally impracticable to dry different thicknesses of timber in a kiln at the same time, different species with similar drying characteristics can be dried in the one kiln charge. Residence time in the kiln depends entirely on the drying rate of the slowest drying piece(s) of timber. Periodic reversals of air circulation help to reduce the lag in drying across the kiln which will tend to be greatest at the centre of the stack in this case. If it is impracticable to identify different species with different drying characteristics, then the drying schedule for stacks of such timber must be chosen on the basis of not causing the most sensitive timber to degrade. The main penalty is the reduced kiln throughput.

Compartment type kilns are relatively expensive to buy and to operate, particularly when the purchase and operating costs of ancillary heat plant are considered. The competent running of such kilns largely depends on having kiln operators who are well trained and experienced in the art of drying timber. Such people are often difficult to find unless special training facilities have been specifically developed for the purpose. Therefore, it is essential to carefully consider whether drying in compartment kilns is the best method or whether one of the less sophisticated methods would be more appropriate for a particular application.

Steaming chamber

Brief reference has already been made to the practice of briefly steaming timber to relieve drying stresses or to recondition collapsed timber. As such a treatment should not be given in any type of drier, mainly because of the risk of corrosion of metal fittings, steaming chambers are used for this purpose.

A steaming chamber is a box-like structure about 600 mm wider and 400 mm higher internally than the timber charge it is required to hold. It is best constructed from reinforced concrete. The only internal fitting required is a 38 mm dia. steam pipe with 6 mm dia. holes at 300 mm centres running centrally along the length of the floor. Steam pressures can be as low as 50 kPa but should not exceed 200 kPa.

Heating of kilns

Steam is the traditional medium used for the heating and humidification of kilns. It is commonly generated from burning green or dry wood residues in boilers operated at pressures of 300-600 kPa or higher. The steam is fed to heating coils, usually of plain or finned piping, running from one end of the kiln to the other end and back again (to minimize any differences in temperature along the length of the kiln). Humidification is usually provided by discharging steam through holes drilled at fixed intervals in a pipe running the length of the kiln.

When oil and gas were much cheaper, automatically operated steam generators were sometimes used instead of wood-fired boilers but high fuel costs now make them uneconomic in most countries. Steam generators have been replaced to some extent by various types of wood-fired furnaces. These are mostly automatically operated and fairly expensive to buy. They may also have special requirements in respect of the size and MC of wood residue fuel that can be used. Some units are suitable for direct firing of kilns with furnace gases whereas others need to be used with heat exchangers to guard against the risk of starting fires inside kilns.

Apart from the heat sources just covered and the possibility of utilizing solar heat to a fairly limited extent, there are few other options available for the heating of kilns. One of the most promising is the current development of direct-coupled wood gasifiers for retrofitting into oil- or gas-fired steam generators or for direct firing of progressive kilns and the like. Another is the use of filtered exhaust gases from wood-residue burners, preferably fed with fuel from a hopper big enough to let it to run overnight without attention.

Moisture content measurement

Two methods are widely used in the timber industry: oven drying and electrical moisture meters. The oven drying method is accurate at all MCs but slow (12-48 h to get a result) unless microwave ovens are used (in a particular way), in which case the time can be reduced to an hour or so. Moisture meters are portable, give instant readings and are fairly accurate from 5-25% if used properly and corrections (for species and temperature) are applied. Purchase costs of hardware for the two methods would be roughly the same.

ABBREVIATIONS

DBT	dry bulb temperature
EMC	equilibrium moisture content
FSP	fibre saturation point
MC	moisture content
RH	relative humidity
WBD	wet bulb depression
WBT	wet bulb temperature

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